EFFECT OF THICKNESS AND BRAND OF METAL

CERAMIC PORCELAIN ON COLOR

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EFFECT OF THICKNESS AND BRAND OF METAL CERAMIC PORCELAIN ON COLOR

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Dedication

To God be the glory through His son Jesus Christ. It is only by His grace that I draw my next breath.

I wish to dedicate this thesis to my wife, Carmen, and my children, A.J. and Emily. Their encouragement, patience, prayers, and sacrifice have made completion of this thesis possible.

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EFFECT OF THICKNESS AND BRAND OF METAL CERAMIC PORCELAIN ON COLOR

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An essential aspect of any successful metal ceramic restoration is to provide an acceptable shade match to adjacent teeth or restorations. Generally, the dentist will select a shade from a prefabricated shade guide and write a work order for the lab to match that shade with the metal ceramic restoration. Two of the many factors that can affect the ultimate shade of a metal ceramic restoration are the brand of porcelain and the thickness of dentin porcelain used in the final restoration.

Some manufacturers claim that new formulations of opaque porcelains are improved because they are "shade-matched" to the

dentin powders to promote a shade match at a decreased porcelain thickness. These porcelain systems have separate opaque powders for each shade in contrast to other "non-shade-matched" porcelain systems that may use the same opaque powder for several shades.

This investigation was designed to examine the effects of thickness and brand on the shade of dentin porcelain. Two hundred eighty-eight metal ceramic specimens were made using a custom shade tab device. Three Vita Lumin shades (A3.5, B1, and C3) of three commercially available dental porcelains that reportedly use shade-matched opaques (Microbond, Ceramco II, and Jelenko) and one commercially available dental porcelain that does not use shade-matched opaques (Vita VMK 68) were used to make six specimens in each of four thicknesses (0.3 mm opaque only, and 0.3, 0.6, and 0.9 mm of dentin porcelain).

Y, X and Z tristimulus values were measured using the HunterLab Colorimeter and converted to CIE L*, a*, and b* color coordinates for each specimen. Seven observers, who tested normal for color acuity, made subjective analyses of representative specimens from each brand-shade-thickness group to rate the level of shade match to a dentin porcelain shade tab. The following results and conclusions can be drawn from this investigation:

1. Significant decreases in L* (value) were noted between thicknesses within most (10/12 or 83%) of the brand-shade combinations evaluated ($p<0.05$).

2. Only two brand-shade combinations (2/12 or 17%) had few (Ceramco II shade A3.5) or no (Ceramco II shade C3)

significant changes in L* (value) between thicknesses of dentin porcelain ($p<0.05$).

3. Significant differences in a* (red-green) values were noted between thicknesses depending on brand and shade ($p<0.05$).

4. Significant differences in b* (yellow-blue) values were noted between thicknesses depending on brand and shade ($p<0.05$).

5. Based on L*, a*, and b* changes, color constancy with increasing thickness of dentin porcelain was dependent on brand and shade. In addition, the porcelain systems that used shade matched opaques did not exhibit more color constancy with increasing dentin porcelain thickness.

6. The L*a*b* variability between different thicknesses of dentin porcelain suggests that manufacturers should recommend specific dimensions for thickness of dental porcelain for each shade to achieve adequate shade matching.

7. Subjective observers found that shade-matched opaques were not more likely to achieve a shade match at thinner dentin porcelain thicknesses than the system that did not have shade-matched opaques.

8. For 83% of the brand-shade combinations, the subjective observers found that 0.3 mm was considered an adequate thickness of dentin porcelain to achieve a closest match to the dentin shade tab (for that particular porcelain).

Increased thickness of dentin porcelain will not necessarily

improve and, for at least one brand-shade combination, may impair shade matching.

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I. Introduction

One function of a metal ceramic restoration is that it mimic the appearance of a natural tooth. That appearance is partially determined by how light interacts with tooth structure. Some of this light may actually be transmitted through the various layers of natural tooth structure (enamel, dentin, and pulp) and not be reflected back to the observer. In contrast, a metal ceramic restoration does not permit this complete transmission, because the underlying metal substructure blocks the passage of light (Yamamoto, 1985). These differences in light interaction between a natural tooth and a metal ceramic restoration pose a challenge to laboratory technicians and clinicians when attempting to create a natural appearing restoration.

Generally, as light strikes a multilayered object, such as a natural tooth or a metal ceramic restoration, it can behave in many different ways. Consequently, it is important to understand the many terms used to describe light behavior such as: incident light, reflected light (both specular and diffuse), refraction, and transmission (both regular and diffuse).

For example, incident light is the light from an external source, such as sunlight or an incandescent light bulb, that strikes an object (Yamamoto, 1985). Reflected light is light that is turned back from the surface of an object. When the angle of incidence is equal to the angle of reflection of light, as in a

mirror, that type of reflection is referred to as specular reflection (McLean, 1979). However, when that light is scattered at a variety of angles and in different directions, as from a rough or matte surface, that type of reflection is described as diffuse reflection (McLean, 1979).

Refraction, on the other hand, is the change in direction of light waves as they pass into and out of an object. When light passes from a vacuum into a material with more density, its velocity is decreased. The ratio between these velocities is called the index of refraction. As the wavelength of the light increases, the index of refraction normally decreases (McLean, 1979).

Transmitted light is the light that passes completely through an object. This effect is generally manifested in two different forms: regular and diffuse transmission. Regular light transmission can only occur if an object is transparent and the light passes through the object (Clarke, 1982). Diffuse transmission occurs when light is scattered within an object while allowing a proportion of this light to pass through the object (Clarke, 1982).

Metal ceramic porcelain can be considered a transparent mass containing small particles with dissimilar refractive indices. Light scattering is the combination of reflection and refraction of light as it passes through such a heterogenous mass. The greatest light scattering occurs when the refractive indices of the transparent mass and the small particles (metallic oxides and grains of differing composition) are most different. Scattering is also dependent on particle size. Maximum scattering occurs when the

particle size is the same as the wavelength magnitude (McLean, 1979).

Opaque porcelain on a metal substructure contains metallic oxides with a high refractive index that can limit the transmission of light to the underlying metal surface (Preston, 1988). Any incident light that reaches this highly reflective opaque porcelain is generally directed back toward the observer. This high reflection is undesirable in metal ceramic restorations because natural teeth allow more light transmission and seldom produce areas of such high reflectivity (McLean, 1979). In addition, if the shade of the opaque porcelain does not match the desired dentin shade, the reflected light may adversely affect the overall perceived shade of the final restoration.

Since the inception of metal ceramic restorations in the late 1950s, five solutions have been proposed in an effort to resolve this problem.

First, dental porcelain manufacturers opted to make the low-fusing dentin porcelain for metal ceramic restorations more opaque, in contrast to more translucent porcelains used for making all ceramic crowns. The intent was to reduce the direct reflection from the highly reflective opaqued metal substructure. It was thought that if the dentin porcelain were made more opaque and diffused more light, then the amount of light that actually reached the opaque porcelain layer would be decreased (Yamamoto, 1985). Furthermore, any light that reached this opaque layer must again be diffused through this same layer of dentin porcelain when reflected

back. The end result of this diffusion being that less light would actually reach the observer.

Second, an alternative approach has been to simply increase the thickness of dentin porcelain overlying the opaque layer (Chiche and Penault, 1988). The influence of direct reflection from the opaque porcelain layer decreases as the translucency of dentin porcelain decreases and its thickness increases (Yamamoto, 1985; Seghi, Johnston and O'Brien, 1986). However, to reduce the detrimental effects from the highly reflective opaque porcelain layer and to provide optimum esthetics, this minimum thickness of dentin porcelain is believed to require 1.3 to 1.5 millimeters of tooth reduction (McLean, 1980; Yamamoto, 1985; Dykema, Goodacre, and Phillips, 1986).

Unfortunately the facial thickness of dentin porcelain is often limited at the cervical margin as well as at the junction of the incisal and middle one-thirds. Attempts to obtain an adequate thickness of dentin porcelain in these two areas often results in an overcontoured restoration that invariably violates the principles of proper form and contributes to periodontal pathology (McLean, 1979; Yamamoto, 1985; Sorensen and Torres, 1988).

Third, modification of the opaque layer has also been suggested as a method to decrease the adverse effects of this highly reflective surface (Yamamoto, 1985; Sorensen and Torres, 1988; Chiche and Pinault, 1988). Opaque modifiers can be used in an effort to more closely match the desired shade in the cervical and incisal areas when insufficient thickness of dentin porcelain is

available (Sorensen and Torres, 1988).

Fourth, modifications of the dentin porcelain, further decreasing the translucency of this layer, have been proposed as another alternative. This technique requires the use of a special porcelain, opacous or opacious dentin, that has greater opacity and chroma and reflects more light than conventional dentin porcelain. The opacous dentins can be blended with conventional dentin porcelains according to the degree of translucency desired to achieve a shade match (Sorensen and Torres, 1988). Unfortunately, decreasing the translucency of the dentin porcelain can result in a less than natural appearing final restoration.

Finally, the summary of recommendations from a workshop on color ordering systems in dentistry, held in November of 1984, contained a fifth possible solution to this problem. That solution was found in the conference conclusions: "In the case of dental porcelain itself, opaque dental porcelains should support body porcelains such that the resultant color is independent of thickness" (Miller, 1988). Other researchers have indicated that opaque porcelain with the same shade as the dentin porcelain (at its optical infinite thickness) will eliminate the effect of variations in dentin porcelain thickness on the overall color (O'Brien, 1985; Jacobs et al, 1987). Some porcelain manufacturers have changed their formulations to match an opaque for each corresponding dentin porcelain (O'Brien, 1985; Farah and Powers, 1985). Unfortunately, no comprehensive investigations have been conducted to date to evaluate the efficacy of these reformulated

metal ceramic porcelain systems with reportedly matched opaque and dentin shades.

II. Literature Review

A. Color Perception

In 1985 Swepston and Miller outlined a series of factors involved in selecting a shade and fabricating a matching metal ceramic restoration. Color perception actually consists of four basic components; a stimulus (light), an object (reflection of light), a receptor (human eye), and an interpreter (human brain). These four factors are discussed at length in other sources (Hurvich, 1981; Preston, 1982; Yamamoto, 1985) but merit a brief discussion.

Light serves as the stimulus for color perception. The wavelengths in the visible electromagnetic spectrum fall between approximately 400 and 700 nanometers (nm) (Hurvich, 1981). Sunlight, tungsten lamps, and fluorescent lamps are three common light sources. Each source emits a specific combination of wavelengths at variable energy levels. For example, blue sky light contains a greater proportion of shorter wavelength components while the light from a tungsten lamp is composed of a greater proportion of longer wavelength components, or red light (Yamamoto, 1985). Most objects are not themselves sources of light but, when viewed, reflect light from another source. Consequently, the spectrum specific energy of the light source will partially determine the nature of the light that is actually reflected from objects. Furthermore, objects of different composition may have the

<u>same</u> appearance when viewed under one light source but have a different appearance when viewed under an alternate light source. This phenomenon is referred to as metamerism.

When light impinges upon a tooth it interacts with all layers of tooth structure. Some light is reflected from the surface of the enamel. So a rough enamel surface will create diffuse reflection while a smooth enamel surface will produce relatively more specular reflection (Muia, 1982). Or a portion of the light may pass from the facial to the lingual surface of the tooth. The light that is transmitted may have an altered path (diffuse transmission) or travel through the tooth at a refracted angle (direct transmission). Where translucent enamel constitutes the total buccal-lingual width of the tooth, such as in the interproximal and incisal regions, very little light is reflected back to an observer. This light is, in fact, directly transmitted and lost to the oral cavity. In the process, areas of the tooth that permit this light transmission appear blue, violet or gray because of the lack of light stimulus reflecting toward the observer (McLean, 1980). The net result is a variety of visual range electromagnetic stimuli reflected from the tooth toward the receptor, the human eye.

The lens structure of the eye serves to focus light stimulus to the back wall of the eye on the retina. The retina contains a network of neural cells that respond to light stimulus by producing an electrical impulse. The receptor cells responsible for color perception are called cones. Early color mixture studies indicated

that three different types of photosensitive materials are necessary to provide color vision (Judd, 1966). There are now data from microspectrodensitometry that establish the existence of three cone photopigments with absorbance peaks at approximately 450 nm, 530 nm, and 560 nm (Hurvich, 1981). These photopigments have been designated $\alpha 450$, $\beta 530$, and $\gamma 560$ (Hurvich, 1981). Light of a given wavelength can be absorbed by each photopigment in variable proportions. It is depletion of these photopigments that accounts for color fatigue after prolonged v`ewing of a colored object. This phenomenon decreases the viewer's sensitivity to certain colors and is the basis for the recommendation to use short glances (5 seconds or less) during shade selection to avoid color fatigue (McLean, 1979).

Other factors in the eye that influence spectral stimulus reception have been outlined by Hurvich (1981). For example, the lens is not perfectly transparent to all wavelengths of light. So 450 nm wavelength light is transmitted through the lens only one-half as much as light of wavelength of 650 nm. Also, as people age, lenses yellow and transmit less of the short wavelength light. Finally, an inert yellow material, the Macula pigment, diffusely covers an area of the retina housing the largest density of cones. The Macula pigment absorbs more of the short wavelength spectral light than mid and long wavelength light. The amount and distribution of this pigment will affect spectral color matching. Because the Macula pigment varies in amount from one individual to the next, it accounts for a large source of the interobserver

variability in making such color matches.

The light stimulus impacts upon the receptor cells of the retina, alters the photopigments, and results in nerve depolarization. This depolarization travels down a pathway through the retina from the receptor (rods or cones) to the bipolar cells and eventually to the ganglion cells which form the optic nerve (Hurvich, 1981). The optic nerves pass through the optic chiasm to the lateral geniculate bodies where optic fibers terminate. Cells of the geniculate bodies give rise to fibers which form the optic radiation to the cortex of the occipital lobes (Clark, 1975). Unfortunately much is still unknown about how the light stimulus finally results in perception or consciousness of color in the cortex of the interpreter's brain. Daw (1987) contends that there are at least 7 levels known in the processing of color vision from receptor to cerebral cortex.

The history of the early development of color vision theories has been summarized by Hurvich (1981) and Zrenner (1983). The early concepts of color vision can be grouped as either the trichromatic vision theory or the color opponent theory (Zrenner, 1983). The trichromatic theory held that the fibers in the optic nerve responded maximally to three different regions in the spectrum; red, yellow/green, and blue/violet. As early as 1867 von Helmholtz wrote that three types of photochemically decomposable substances are in the end organs of the fibers of the optic nerve each having a different sensitivity for the different parts of the spectrum (Zrenner, 1983). Subsequent work with this theory led to modern

colorimetry (Zrenner, 1983).

Zrenner (1983) indicated that Hering proposed the opponent color theory in 1878. Hering theorized that there are six basic sensations recurring in opponent pairs, red/green, blue/yellow, and black/white. The opponent color theory would predict the existence of on-red off-green, off-red on-green, on-yellow off-blue, and off-yellow on-blue opponent color cells. Present data support the existence of these cells (Daw, 1987).

As early as 1882, von Kries suggested that both color theories might have validity. Vision could be trichromatic at the receptor level while opponent processes occur in the postreceptoral neural pathways (Zrenner, 1983). Evidence from colorimetric data and electrophysiological studies of the retina support this integration of both theories. Absorption of light stimulus in each of the three photopigments excite the white/black neural system. In addition, the α450 and γ560 excite red in common and the β530 and γ560 excite yellow in common (Hurvich, 1981). Receptors converge onto opponent color cells and opponent color cells converge at higher levels onto double opponent cells. These opponent color cells have an excitatory input from one type of receptor and an inhibitory input from another (Daw, 1987).

Another important factor in color perception is the organization of receptors and their subsequent pathways into receptive fields. These receptive fields are concentrically organized cell by cell, on an opponent color basis (Davson, 1980). The organization of receptive fields is responsible for allowing

clear delineation of sharp edges and contours at the cognitive level (Hurvich, 1981).

In summary, all of the details of human color perception are not known at this time. The stimulus from the visible electromagnetic spectrum that is reflected off of an object reaches the retina of the eye where it impinges on the trichromatic cone receptors. Action potentials are generated that can both inhibit and excite a complex neuronal network that culminates as perceived color at the conscious level.

B. Color Order Scales

In 1931 Clark introduced the application of the Munsell Color Order System for the description of color in dentistry. Clark reviewed the three dimensions of color as outlined by Munsell; hue, brilliance and saturation (Clark, 1931 and 1933; Munsell, 1961). Hue being that dimension that permits colors to be classified as reddish, yellowish, greenish or bluish, etc. Brilliance was defined as the range from darkest (black) to lightest (white) and has also been called value, brightness, or luminance. Saturation indicates the strength of the hue as seen in the color that Clark termed chroma. Neutral gray being zero in the saturation scale, and the spectrum furnishes a maximum saturation for all hues (Clark, 1933).

Munsell arranged the attributes of hue, brilliance, and

saturation in three dimensional color space with equal steps from one color to another. In this way, a color could be numerically defined and the distance in color space between two colors could be measured. Hunter (1975) outlined the development of as many as 30 color ordering systems. He stated that the development of these systems had paralleled the formulation of color vision theories.

Another color system of great importance is the C I E (Commission Internationale de L'Eclairage) standard observer system. The first major recommendations regarding colorimetric standards were made by the CIE in 1931 and these formed the basis of modern colorimetry (Publication CIE No. 15, 1971). The CIE is a psychophysical system incorporating a standard observer and coordinate system (Lemire and Burk, 1975). The standard observer is a mathematical description of the average normal human visual response to color stimulation based on experiments by W. D. Wright in 1928 and J. Guild in 1931 (Hunter, 1975). The CIE system also includes standard illuminants A, B, C, D_{55}, D_{65}, and D_{75} with specified spectral distribution curves (Clarke, 1982). As more accurate information has become available, the CIE standards have been periodically updated (Publication CIE No. 15, 1971).

The basic CIE concept is that colors can be matched by some mixture of three light primaries; red (X), green (Y), and blue (Z) (Lemire and Burke, 1975). These X, Y, Z data are called tristimulus values. Luminance or value is included in only one of the tristimulus values, Y, and not in either the X or Z quantities. Furthermore, all of the tristimulus values are linear

transformations of the spectral absorption curves of three cone pigments found in the retina (Clarke, 1982).

One problem with application of the tristimulus X, Y, Z system to surface color evaluation in industry is the subjective nonuniformity of the color space (Hunter, 1975). In response to this problem CIE developed the L* a* b* system based on nonlinear transformations of the X, Y, Z system (Clarke, 1982). Luminance (value) is designated by L* values. The a* represents the red-green axis with negative values indicating green and positive values indicating red. The b* represents the blue-yellow axis with negative values indicating blue and positive values indicating yellow. This CIE L* a* b* system is widely used in science and industry to express color differences. The distance between any two colors in this color space (ΔE) is defined by the following equation (Hunter, 1975):

$$\Delta E = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2}$$

Hunter (1975) stated that color differences, as defined by this equation, are not reliably correlated with visual estimates of color difference.

Hunter (1975) also outlined three factors proposed by L.F.C. Friele that would explain why these tristimulus color differences fail to consistently correlate to visual color estimates. The first factor was that the magnitude of color difference is more properly related to the component of the particular difference that is greatest. Similarly, Preston (1982) pointed out that because

the human observer is very sensitive to slight differences in value, a small change in value could be perceived as equal to a larger change in hue. The second factor that Friele proposed was that threshold discrimination differences correspond to minimum detectable signal-to-noise ratios in the neural signaling system while estimates of easily seen differences correspond more closely to the actual signal increments. Basically, small changes in color are detected less effectively, because they may be confused with baseline stimuli. The third factor was that the numerical tristimulus values may be correctly integrated with reception spectral responses but fail to be valid measurements of post receptor neural signals. For these reasons many investigators have evaluated color differences by both subjective observers and tristimulus colorimeter readings.

An evaluation by Kuehni and Marcus (1979) attempted to correlate color difference formulas including the CIE L*a*b* (ΔE) system with the subjective observer's perception. Observers were asked to rate colored samples as either an acceptable or not acceptable color match with a standard. The average total ΔE for 50% acceptibility was approximately one unit. Of the four color difference formulas evaluated, each produced the highest correlation with subjective observers for at least one of the six sample sets. The authors concluded that additional visual small color difference data are needed to develop a new formula that consistently correlates to human visual perception.

Johnston and Kao (1989) compared a United States Public Health

Service visual ranking scale used by subjective observers to the CIE L*a*b* ΔE formula. The average color difference between compared teeth rated as a match was 3.7 units. Thus, significant differences exist in CIE L*a*b* color space that apparently are not discernible to subjective observers.

The arguments proposed by L.F.C. Friele and the studies by Kuehni and Marcus (1979) and Johnston and Kao (1989) pointed out that no direct numerical correlations existed between small color difference formulas and the human perceptual experience.

C. Color Measurement

Two basic types of color measuring instruments are the spectrophotometer and the tristimulus colorimeter. Spectrophotometers measure reflectance or transmittance factors one wavelength at a time while tristimulus colorimeters measure reflectance or transmittance of three broad wavelengths that are roughly equivalent to the red, green, and blue response of retina cone receptors (Hunter, 1975).

Goodkind et al. (1985) compared the ability of a tristimulus colorimeter and a recording spectrophotometer to predict the closest color match by subjective observers for 100 extracted human teeth. Neither instrument was shown to agree significantly more closely with human observation. Hunter (1975) concluded that tristimulus colorimeters will give precision in color measurements of the same order of magnitude as a recording spectrophotometer.

In addition, Hunter stated that tristimulus colorimeters and reflectometers could provide more precise and less expensive means for the intercomparisons of small color differences. As early as 1967, Judd and Wyszecki concluded that near white vitreous enamel specimens could be measured accurately with the Hunter colorimeter.

Other variables controlled by CIE standards are the illuminating and viewing conditions of the measuring instrument (Publication CIE No. 15, 1971). The light striking an object may vary from 0° (normal incidence) to 90° (grazing incidence) or may strike the object in a diffuse manner from many directions at once (Clarke, 1982). The four geometries recommended by CIE are: 0° illumination with diffuse reflectance viewing, diffuse illumination with 0° viewing, 0° illumination with 45° viewing, and 45° illumination with 0° viewing.

Seghi (1990) evaluated the effects of different measuring geometries on the colorimetric assessments of dental porcelain. His results indicated that although the values obtained on the bidirectional instruments were not the same as those obtained on the diffuse-type reference instruments, the relative values obtained between the instruments remained consistent. A high degree of correlation existed between color difference measurements regardless of the design of the instrument measuring geometry.

D. Composition of Metal Ceramic Porcelain

The composition of metal ceramic porcelains has been described

by McLean (1979), Binns (1982), Yamamoto (1985), and Naylor (1986). Metal ceramic porcelains are alumino silicate glasses composed primarily of 75-81% feldspar, 15-25% quartz, 0-4% kaolin (if present), and varying amounts of fluxes (Yamamoto, 1985). Feldspar is a naturally occurring mineral composed of soda (N_2O), potash (K_2O), alumina (Al_2O_3), and silica (SiO_2) (Phillips, 1991).

Naylor (1986) has summarized the qualities of the two naturally occurring feldspars; potash feldspar and sodium feldspar. Since natural feldspar varies in composition, the ratio of potash to soda could vary. The characteristics which each imparts to the porcelain are different and therefore this ratio is controlled by the manufacturers. Upon melting, the feldspar becomes a vitreous mass with high viscosity and transparency. Potash enhances the translucent qualities and increases the viscosity, thus helping to control the pyroplastic flow of the porcelain during the firing process. Sodium feldspar lowers the fusion temperature of the porcelain making it more susceptible to pyroplastic flow. In addition, sodium feldspar does not contribute to the translucency, as does the potash form.

Embedded in this vitreous mass is a refractory framework of quartz (silicic anhydride) that reduces translucency and increases strength (Yamomoto, 1985). Potassium, sodium, calcium and boric oxides may be added as fluxes to lower the melting range and decrease viscosity (McLean, 1979).

Metal ceramic porcelain is classified as a low-fusing porcelain, with firing temperatures between 800° C and 1,050° C

(McLean, 1979). Compared to high- and medium-fusing porcelains, these low-fusing porcelains contain higher soda and potash levels in order to raise their thermal coefficient of expansion and be physically compatible with a metal substructure (McLean, 1979).

The process for manufacturing dental porcelain powders includes an initial high temperature sintering of the raw mineral constituents (feldspar, silica, alumina and other trace components). A molten glass is formed that is quickly cooled and shattered into fragments during what has been described as a fritting process. These colorless particles, or frits, are ground to specific particle sizes and combined with other frits containing pigmented metallic oxides. Opacifying agents are added in varying amounts according to the specific functional or color related role that is desired (Phillips, 1991). Thus, opaque porcelains contain the highest levels of opaque oxides and enamel or translucent porcelains contain the least.

For example, the opaque porcelains that are applied to the oxidized metal surface contain relatively higher amounts of crystal phases of the tetravalent metal oxides TiO_2, SnO_2, ZrO_2, CeO_2, and zircon (Binns, 1982). These components have relatively high refractive indices and may be used in amounts as high as 8-10% (Binns, 1982). Particle sizes vary from 0.4 to 0.8 μm and may be incorporated into the original fritting process to prevent segregation and localized concentrations of color and opacity (McLean, 1979).

E. Factors Affecting Metal Ceramic Porcelain Color

Many of the manipulative steps in fabricating a metal ceramic restoration have been evaluated for their effects on the color parameters of the final restoration. Some of these factors include: type of alloy for the metal substrate, surface finish of the metal substrate, porcelain condensation technique, type of modeling liquid used, brand of porcelain, thickness of porcelain, air-firing versus vacuum-firing, firing rate, firing temperature, and number of firing cycles.

Gettleman and others (1977) spectrophotometrically evaluated the effect of three metal surface treatments (600 grit finish, sandblasting with pumice, and the application of a gold flash conditioning agent) on the masking power of opaque porcelain. They concluded that samples that were gold flash conditioned required 40 to 60% less opaque porcelain thickness to achieve the same spectral reflectivity as the specimens that were not gold flash conditioned.

Brewer and others (1985) spectrophotometrically measured the color of one shade (A2) of Vita VMK 68 porcelain during seven fabrication steps of firing onto three alloys (palladium-silver, nickel-chromium-beryllium, and a high gold content alloy). The mean tristimulus values were significantly different between the alloys and these differences were most pronounced after the first dentin firing. The authors concluded that without subjective observation these quantitative differences yield no indication of the clinical significance of these results.

Jacovides and others (1985) reported on the ability of a 0.1 mm layer of four opaque porcelains to mask six high palladium alloys. Quantitative color values were measured with the Chromascan colorimeter and a limited human visual evaluation was performed. The authors concluded that substructures produced from some high palladium alloys would require a thicker layer of opaque to mask their underlying oxide layer.

Jacobs and others (1987) visually and spectrophotometrically evaluated color differences between samples fabricated with three metal ceramic alloys (gold-platinum-palladium, nickel-chromium, and high-palladium) and three shades (A3, B1, and C4) of Vita VMK 68 porcelain at three dentin porcelain thicknesses (0.5, 1.0, and 1.5 mm). They observed that subtle differences in color were noted more often with the human eye than with the spectrophotometer. Significant differences in hue were variable between the three alloys and were more pronounced with one particular shade, A3. Furthermore, significant differences in color were noted with increasing thickness of dentin porcelain and these differences were more pronounced with two shades of porcelain, A3 and C4. The authors concluded that when opaque porcelain color more closely matched the dentin porcelain color (B1), a shade match could be achieved with less overall porcelain thickness.

Two different alloys (high-gold and base metal) and four different alloy surface finishes (60, 180, and 600 grit, and 180 grit with surface conditioner) were evaluated by tristimulus colorimeter, spectrophotometer and human visual observation for

color differences after porcelain application in a study by O'Neal et al. (1987). One shade (69) of Ceramco porcelain was applied at 0.15 mm of opaque and 1.0 mm of dentin porcelains. The authors concluded that color differences were small and probably not clinically significant at this porcelain thickness. Most of the color differences between specimens with different surface finishes were due to hue and chroma shifts. There was a visually significant difference in chroma between specimens fabricated with the two different alloys. The authors postulated that the observed color differences could be more pronounced at decreased porcelain thicknesses. While this is possible it was not substantiated by their study.

Brewer et al. (1989) evaluated CIE tristimulus color order differences between metal ceramic coupons fabricated with a high-gold content alloy and those fabricated with a palladium-silver alloy. A single shade of two porcelains was used, Vita VMK 68 and Vita VMK 68 N. The mean tristimulus values were different for coupons fabricated with different alloys and with different porcelains. For final color, non-greening Vita VMK 68 N had higher a* (more red) and lower b* (less yellow) for both metals. Correlation with human visual perception was not mentioned.

Condensation of porcelain has been shown to effect color parameters for metal ceramic restorations. Condensation can be achieved by vibration, spatulation, and brush techniques (Phillips, 1991). Less thorough condensation is thought to result in the inclusion of more air bubbles in the fired porcelain and a decrease

in translucency (Yamamoto, 1985).

Evans (1988) evaluated four condensation methods with one shade (B2) of four ceramic porcelains (Ceramco II G series, Will-Ceram V series, Vita VMK 68, and Jelenko) by tristimulus colorimeter and subjective observers. Porosity was evaluated by measuring the apparent specific gravity of each specimen and no significant differences between condensation methods were noted. All four porcelains exhibited significant differences between condensation methods for a* and b* color data. Will-Ceram and Vita VMK 68 porcelains exhibited significant differences in color between condensation methods as measured by subjective observers. While all four porcelains reportedly were manufactured to match the Vita B2 shade guide, they were significantly different as measured by CIE L*a*b* values and subjective observers.

A 1978 study by Barghi and Richardson used six subjective observers to evaluate color of one porcelain fired on four alloys (Ceramco R, SMG-2, Bak-On, and Will-Ceram). In addition, color was assessed for change after 1 through 8 repeated firings. Surfaces of the finished metal and fired porcelain were evaluated by scanning electron microscopy. The evaluators reported no color differences between the porcelain on the four different alloys. Color was stable for six firings and chroma was reported to increase only slightly after nine firings. However, the authors did not indicate how the observers rated the color of the specimens.

Kay and others (1989) spectrophotometrically evaluated CIE L*a*b* changes of the two shades of five brands of porcelain after

one and six firings. Composite disks of opaque (1.05 mm) and body porcelain (1.00 mm) were fabricated without metal substructures. The authors concluded that the majority of observers could have noticed color changes (ΔE) of 1.74, 1.75, and 3.52 recorded for three brands of dental porcelain but not the 0.88 for the other two brands. This finding is not in agreement with the observations of Johnston and Kao (1989) and no subjective observers were involved in this evaluation.

Barghi and Goldberg (1977) used subjective observers to evaluate color changes after repeated firings in both air and under vacuum using one brand (Ceramco) of dental porcelain on platinum foil. For the first five firings the observers could not detect any color differences between and within either air- or vacuum-fired samples. Between the fifth and tenth firings small decreases in value were observed for the vacuum-fired porcelain while the air-fired porcelain exhibited a greater decrease in value with slight increases in chroma. It was postulated that the greater color changes for the air-fired porcelain could be attributed to a decrease in the number and size of air bubbles after repeated firings.

Then in 1982, Barghi evaluated the effect of additional firings on the color of four brands of porcelain fused to six different alloys. The specimens were fired from one to nine times at glazing temperatures. Seven subjective observers reported some slight color changes after the fifth through the ninth firings but the author concluded that these changes were not significant.

Lacefield and others (1985) used both subjective observers and a colorimeter to evaluate color changes in 0.1 mm of opaque and 0.75 mm of body porcelain fused to four high palladium alloys (palladium-silver, palladium-copper-gallium, palladium-gallium-cobalt, and gold-palladium) after five firings in addition to the original firings to fabricate the samples. Statistically significant decreases in value were recorded by colorimeter for all four alloys after additional firings. Subjective observers reported significant color differences between both the palladium-gallium-cobalt and palladium-copper-gallium alloy-porcelain disks before and after the additional firings. Energy dispersive spectroscopy was used to determine the extent of metal diffusion into the porcelain. The authors concluded that the presence of high concentrations of certain metals (such as gallium) in the porcelain may account for the reduction of value after additional firings.

Schultz and others (1989) used a colorimeter to evaluate color changes affected in dental porcelain (American Thermocraft shade A-2) by different firing rates of 50°F/min (Group A), 100°F/min (Group B), and 200°F/min (Group C). Statistically significant differences in ΔE units were found between all three groups (A-B= 1.74, A-C= 2.02, and B-C= 0.28). However, metal substructures were not used and the ability of human observers to perceive these differences was not established.

Hammad and Stein (1991) colorimetrically evaluated color changes affected by variable firing temperatures (recommended temperature, recommended temperature plus 35°F, and recommended

temperature plus 70°F), number of firings (5, 7, and 9), alloy type (Olympia and Talladium), and porcelain brand (Vita VMK 68 and Ceramco II). There were significant increases in hue and decreases in value but no changes in chroma when firing temperatures were increased. There were no significant changes in hue, value, or chroma when the number of firings were increased from five to nine. Significant differences were noted in hue, value, and chroma between the two porcelain brands evaluated. The effect of changing the alloy type on hue, value, and chroma varied with the porcelain brand used at a given firing temperature. Again, subjective observers were not employed and therefore the question of whether or not these changes could be visually perceived remains unanswered.

Seghi and others (1986) used a spectrophotometer to evaluate color differences between three brands (Vita VMK 68, Crystar, and Biobond) of four shades (A1, B2, C4, and D3) of porcelain. Metal substructures were not used and the opaque and dentin porcelains were fired separately in large samples, sectioned, polished, and placed in optical contact for color analysis. Significant differences in CIE L*a*b* values were noted between different brands of the same shade of porcelain. Greater color differences existed between corresponding shades of opaque porcelains than between corresponding shades of combined opaque-body porcelains. The addition of 1 mm of body porcelain in optical contact with the opaque porcelain compensated to a large extent for the greater color differences found between the corresponding opaques. The lack

of organized subjective observation and the unorthodox method of sample fabrication make application of these results to the clinical environment questionable.

Barghi and Lorenzana (1982) used subjective observers to evaluate color changes affected by variations in opaque porcelain and dentin porcelain thickness of six shades and of two brands of metal ceramic porcelain (Vita VMK 68 A1, B1, and C1; Ceramco shades 59, 61, and 81). The thickness of opaque and body porcelain that produced optimal shade matching varied between shades and porcelain systems. Additional opaque porcelain in excess of 0.3 mm had no discernible effect on the shade of the specimen. Similar results were also obtained in a study by Terada et al. (1989b). They fused 0.5 mm of Vita VMK 68 shade A2 opaque porcelain to four different metal ceramic alloys and measured color differences in CIE L*a*b* color space as the opaque thickness was reduced. Variations in CIE L*a*b* values were not significant until the opaque thickness was below 0.3 mm.

A 1988 study by Rosenstiel and Johnston evaluated the effect of firing temperature, condensation technique, type of modeling liquid, brand of porcelain, and shade of porcelain on color of metal ceramic restorations as measured in CIE L*a*b* color space. Their results indicated that color differences associated with different modeling liquids, differences in firing temperatures of 30°C, and different condensation techniques were not statistically significant. The authors concluded that the recorded differences had a ΔE of 1 or less and were probably not visibly detectable.

However, significant differences in ΔE were noted between different shades of porcelain as well as between different brands of porcelain of the same nominal shade.

Terada and others (1989a) evaluated differences in CIE L* a* b* color space between Vita VMK 68 shade A2 metal ceramic specimens fabricated with 0.1 mm, 0.2 mm, and 0.3 mm of opaque porcelain with 0.1 mm or 0.5 mm of dentin porcelain fired over the opaque porcelain. L* decreased in all samples as the thickness of dentin porcelain increased. Redness (a*) increased for all samples as the dentin porcelain thickness was increased and yellowness (b*) increased for most samples as the dentin porcelain thickness was increased. There were significantly different ΔE values between samples having 0.2 and 0.3 mm of opaque porcelain when covered with each of the thicknesses of dentin porcelain using a nickel-chromium alloy.

Jorgensen and Goodkind (1979) used a spectrophotometer to determine hue, chroma, and value differences associated with repeated firings (2, 5, and 10) and three thicknesses (1, 2, and 3 mm) of dentin porcelain of three shades (A3, B2, and D3) of three brands of porcelain (Ceramco VT, Vita VMK 68, and Biobond). Opaque porcelain of 0.1 mm thickness was fused to a gold-palladium-silver alloy and then covered with 1, 2, or 3 mm of dentin porcelain and fired again. No statistically significant differences in hue, chroma, or value were noted for the different thicknesses of dentin porcelain. Value increased as thickness of dentin porcelain increased. This is exactly opposite the decrease in value

associated with increasing thicknesses found in many other studies (Moser and Meyer, 1983; Jacobs et al., 1987; and Terada et al., 1989a). One possible explanation for the observation could be that this study used only 0.1 mm of opaque over a metal ceramic alloy. If the alloy oxide layer was dark and the 0.1 mm of opaque was insufficient to mask this darkness then the value would be low to begin with. As more porcelain was added to cover the opaque layer the added reflective properties of the dentin porcelain decreased the affect of the underlying dark oxide layer on the color resulting in a net increase in value.

In 1989, Johansen and others evaluated the differences in color (ΔE) between an unidentified porcelain fired at three different glazing temperatures that were increased in increments of 50°F starting at 1750°F and ending at 1850°F. Statistically significant differences in ΔE were noted between the different temperatures. The authors concluded that with increased temperature of glazing there was a shift toward the blue-green color axis and overall darkening. Neither metal substructures nor subjective observers were employed therefore clinical applicability of the findings are questionable.

Obregon and others (1981) studied the effects of various opaque and dentin porcelain surface textures of two shades (A3 and B1) of Ceramco G porcelain on color as measured by a spectrophotometer. Changes in dentin porcelain surface texture had no significant effects on hue and chroma. However, rougher dentin porcelain surface finish resulted in a slight increase in value for

shade A3 and a decrease in value for shade B1. Yet, there were significant differences in hue, chroma, and value between glossy and rough opaque porcelain surface finishes.

F. Summary

Many of the studies evaluating color of metal ceramic porcelain systems have used methods that preclude an application of the results to the clinical setting. For example, the study designs may not have included ceramic specimens with metal substructures, they may have used thicknesses of porcelain that could not be achieved in a dental restoration, or the investigators failed to evaluate color changes with human observers. Other studies have limited application to clinical settings because only one shade of porcelain was evaluated.

Some porcelain manufacturers claim that new formulations of opaque porcelain are improved because they are "shade-matched" to the dentin porcelain to promote overall restoration shade match at thinner porcelain thickness. These porcelain systems have separate opaque porcelain powders for each shade (eg. Microbond, Ceramco II, and Jelenko) in contrast to other ("non-shade-matched") porcelain systems that may use the same opaque powder for several shades (eg. Vita VMK 68).

If this is true, changes with increasing thickness of dentin porcelain in L*, a*, and b* values for those porcelain systems with "shade-matched" opaques would be expected to be less than changes

for "non-shade-matched" opaques. In addition, it is expected that human observers would perceive a shade match at less thickness of dentin porcelain for specimens made with a "shade-matched" opaque system than specimens made with a "non-shade-matched" opaque system.

Consequently, this study was undertaken to evaluate the contention that metal ceramic porcelain systems with "shade-matched" opaques achieve a shade match with less dentin porcelain thickness than systems without "shade-matched" opaque porcelains.

III. Materials and Methods

Three Vita Lumin shades (A3.5, B1, and C3) of three metal ceramic porcelains with shade matched opaques (Ceramco II, Ceramco, Inc., Dentsply International Inc., York, PA; Microbond, Nobelpharma USA, Inc, Chicago, IL; and Jelenko, J. F. Jelenko and Company, Penwalt Corp., Armonk, NY) and one metal ceramic porcelain without shade matched opaques (Vita VMK 68, Vident, Baldwin Park, CA) were fired to gold-palladium alloy disks in four thicknesses (0.3 mm of opaque only, and opaque with 0.3, 0.6, and 0.9 mm of dentin porcelain). Six specimens were made for each brand-thickness-shade combination for a total of 288 samples. For an objective analysis of color difference, the color of the specimens was evaluated with a colorimeter, recorded as Y, X, and Z tristimulus values. CIE L*a*b* values were then calculated and used for the statistical analyses. Seven subjective observers rated representative specimens from each brand-thickness-shade group for color match with a dentin shade tab to obtain a subjective assessment of color differences for A3.5, B1, and C3.

All specimen fabrication and testing procedures were conducted to closely approximate the actual laboratory construction and clinical use of metal ceramic restorations. Samples were prepared in two phases: 1) fabrication of the metal substructure, and 2) the application and firing of the dental porcelain onto the substructure.

A. Fabrication of the Metal Substructures

The two hundred and eighty eight disks, 10 mm in diameter, were cut from 0.508 mm thick acetate plastic sheets (Temporary Splint Material, Buffalo Dental Mfg. Co., Inc., New York, NY). A 10 mm long piece of 10 gauge plastic sprue former (Plastic sprues, Williams Dental Co. Inc., Amherst, NY) was luted to the center of one side of each disc and cast to serve as a handle for ease of manipulation. Eight patterns were connected to a rubber crucible former on a preformed wax runner bar (Wax Ready sprues, 013117 large, Belle de St. Claire, Chatsworth, CA) (Plate 1). The specimens were invested with a high-heat, phosphate-bonded casting investment (Vestra-fine, Unitek Corp./ 3M, Monrovia, CA) using 195 gms of powder with a mixture of 23.25 ml of distilled water and 23.25 ml of Vestra-fine special liquid. The casting rings were allowed to bench set for one hour and placed in a cool burnout oven. The oven temperature was raised to 316°C at a rate of 4°C/minute and held for 45 minutes. Then the oven temperature was raised to 815°C at the same rate of rise and heat soaked for one hour. After wax elimination, the substructures were cast with a high noble gold-palladium alloy (Olympia, 51.5% Au and 38.5% Pd, Penwalt Jelenko, Armonk, NY).

The castings were divested and cleaned manually (Plate 2), then cut from the runner bar with silicon carbide separating discs (Dedeco No. 5178, Dedeco International Inc., Long Eddy, NY). The top surfaces of the castings were finished sequentially on 240,

320, and 400 grit silicon carbide paper strips (Carbimet paper strips, Buehler Ltd., Lake Bluff, IL) under a water stream in a surface grinding device (Handimet Grinder, Buehler Ltd, Lake Bluff, IL). The metal substructures were numbered on the sprue stem for ease of identification (Plate 3). Also, four equally spaced depressions were placed on the specimen's undersurface for thickness measurement indices (Plate 4). An angled notch was cut approximately 1 mm from the distal end of the sprue stem where ligature wire could be used to hold the substructure in place during porcelain condensation (Plate 5). The castings were air-abraded with 25 micrometer aluminum oxide (Faskut Aluminum Oxide Abrasive, Dentsply/York Division, York, PA) at 50 psi, and steam cleaned for 10 seconds.

Finally, the substructures were oxidized in a calibrated porcelain furnace (Ultramat CDF, Unitek Corp./3M, Monrovia, CA) to 1040°C in air with no hold time in groups of six. The specimens were then air-abraded with 25 micrometer aluminum oxide as above and steam cleaned just prior to porcelain application (Plate 6).

B. Porcelain Application

All four of the metal ceramic porcelain systems used in this investigation reportedly are matched to the Vita Lumin shade guide (Vita Zhanfabrik, Bad Sackingen, Germany). For added clinical relevance, each manufacturer's recommendations were followed for all porcelain firing sequences (Appendix A).

For consistent thickness of porcelain a commercially available custom shade tab device (Gnathos Shade Tab Former, Belle de St. Claire, Chatsworth, CA) was modified to accommodate the handle on the specimen (Plate 7). The custom shade tab device has a scale on the side to allow for repeatable adjustment of depth (Plate 8). To provide optimum masking of alloy, the opaque was applied and sintered in two separate firings to a thickness of approximately 0.3 ± 0.02 mm (Barghi and Lorenzana, 1982; Terada, Sakai, and Hirayasu, 1989b). The body porcelain was also applied in two separate applications and firings. The depth of the mold was adjusted so that the thickness of dentin porcelain measured 0.4, 0.7, or 1.0 mm after firing to allow for a loss of approximately 0.1 mm of dentin porcelain during finishing.

Before each porcelain application the specimens were steam cleaned for five seconds. The metal substructures were placed in the mold and 15 gauge ligature wire was passed through the notch in the sprue stem to hold them firmly in place during porcelain condensation (Plate 9). Opaque and dentin porcelain were placed in the mold with a brush (Plate 10), levelled with a spatula, condensed by vibration with a serrated handle, blotted dry with facial tissue, and smoothed with a dry brush (Plate 11). Vita opaque was mixed with Paint-On Liquid (Vident, CA) and Vita dentin porcelain was mixed with Vita Modelling Liquid (Vident, CA). Ceramco opaque porcelain was mixed with Opaque Liquid (Dentsply International Inc., PA) and the Ceramco dentin porcelain was mixed with Body Liquid (Dentsply International Inc., PA). Microbond and

Jelenko porcelains were mixed with distilled water as per the manufacturer's directions. Before each application of porcelain the specimens were steam cleaned for 10 seconds. Thicknesses were recorded for each of the four index sites on every specimen using a dial caliper accurate to within 0.01 mm (Praecimeter, Pfingst and Company, Inc., South Plainfield, NJ) (Plate 12) at three fabrication stages; oxidized metal, final opaque, and final glaze. All specimens with dentin porcelain were serially finished with 240, 320, and 400 grit silicon carbide paper strips (Carbimet paper strips, Buehler Ltd., Lake Bluff, IL) under a water stream in a surface grinding device (Handimet Grinder, Buehler Ltd, Lake Bluff, IL) to dentin porcelain thicknesses of 0.3, 0.6, or 0.9 ± 0.02 mm. Before glazing, the specimens with dentin porcelain were again air abraded with 25-μm aluminum oxide for 10 seconds and again steam cleaned for 10 seconds.

C. Color Measurement

1. Tristimulus Colorimetry

Color measurements on the samples were made with a tristimulus colorimeter (HunterLab Colorimeter D25A-2, Hunter Associates Laboratory, Inc., Reston, VA) and recorded as Y, X, and Z tristimulus values. The sensitivity of this instrument is reported at 1% for measurement of diffuse reflectance (HunterLab Associates Laboratory, 1980). Color values are repeatable ± 0.1 and

reproducible ± 0.2 scale units. Color values are accurate to a root mean square deviation of 0.7 scale units (referenced to CIE illuminant C 1931, 2° observer values assigned to master reflectance standards) (HunterLab Associates Laboratory, 1980).

The HunterLab D25A-2 Colorimeter features dual beam 45° illumination and 0° viewing (Plate 13). Light from a tungsten halogen lamp is split into two beams, which are filtered to prevent infrared sample heating. This light is then reflected onto the sample in two opposing beams at an angle of approximately 45°. Light reflected from the sample is collected at 0° and directed to four filters and four photodetectors. The source-filter-detector combination simulates the CIE 2° standard observer functions under illuminant C.

Prior to each data gathering session the instrument was standardized using first black and then white tile standards (Hunter Associates Laboratory, Inc.). The HunterLab Standards are traceable to measurements at the National Bureau of Standards (U.S.A.) and the National Physical Laboratory (Great Britain). Since Y, X, and Z tristimulus values are not readily described in human color perception terms, these values were converted to CIE L* (luminance), a* (red-green), and b* (yellow-blue) notation using the recommended mathematical formulas (Appendix B).

2. Subjective Observer Analysis

For subjective observer analysis, seven observers (3 female

and 4 male) were evaluated at the Visual Electrodiagnostic Laboratory, Clinical Sciences Division, Brooks AFB, Texas by an individual with a doctorate degree (PhD) in ocular electrophysiology. Evaluation included two anomaly tests, the Pseudoisochromatic Plate (PIP) test and the Anomaloscope Plate Test (APT 5), and one hue discrimination test, the Farnsworth-Munsell 100 Hue discrimination (FM 100 H) test. All observers had color vision within normal limits.

A representative sample from each brand-thickness-shade group was selected by choosing a specimen with L*a*b* values that most closely approximated the mean L*a*b* values for the group. A single representative sample was selected to minimize color fatigue of the subjective observers by reducing the number of color matchings. A neutral gray mat board was prepared for each shade (3 boards) with 16 equally spaced 10 mm diameter holes. All of the selected specimens from one shade were randomly picked from a bag and mounted in the holes on a single panel (Plate 13). Each specimen was mounted from the back of the panel so that the observers could not see the thickness of the specimen. The individual observers made their observations in a room illuminated with artificial, full-spectrum, color-corrected lighting (Vita-Lite, Duro-test Corporation, North Bergen, NJ) at a light intensity of approximately 79 footcandles. Each observer was given a tabulation sheet and asked to score each sample for its level of matching of specimen to a dentin shade tab (Vident). The scale used ranged from 1 to 5: 1=sample was not at all the same, 2=somewhat the same, 3=

moderately the same, 4=nearly the same, or 5=exactly the same.

D. Statistical Analysis

The L*, a*, and b* data were analyzed with a three factor Analysis of Variance (ANOVA) for each of the color parameters (Jacobs et al., 1987 and Evans, 1988). The first factor was brand of porcelain, the second factor was thickness of dentin porcelain, and the third factor was shade of porcelain. Tukey's Studentized Range Tests were used to make multiple pairwise comparisons between thickness of each brand-shade group.

Interrater reliablility was assessed for the subjective observers by the alpha coefficient analysis. Coefficient alpha is the expected correlation of one rating with another rating of the same length when the two tests purport to measure the same thing (Nunnally, 1967).

The subjective rankings were totalled and a mean rank determined. A Kruskal-Wallis analysis of the ordinal level rank order data for both thickness and brand was performed at a significance level of $p < 0.05$. Non-parametric multiple pair-wise comparisons of thickness for each porcelain shade were made using the Mann-Whitney Rank Sum Test at a significance level of 0.05 (Evans, 1988). Based on the initial comparisons between thickness, selected mean specimens were compared between brand within each shade using the Mann-Whitney Rank Sum Test ($p<0.05$).

Plate 1. Acetate plastic patterns connected to plastic sprue formers, runner bar, and crucible former.

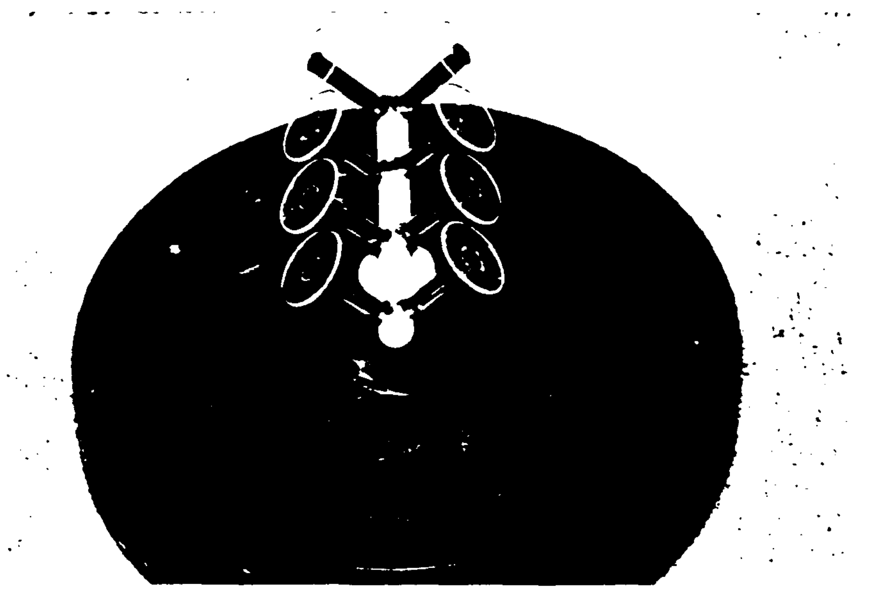

Plate 2. Representative example of metal substructure castings just prior to removal from the runner bar.

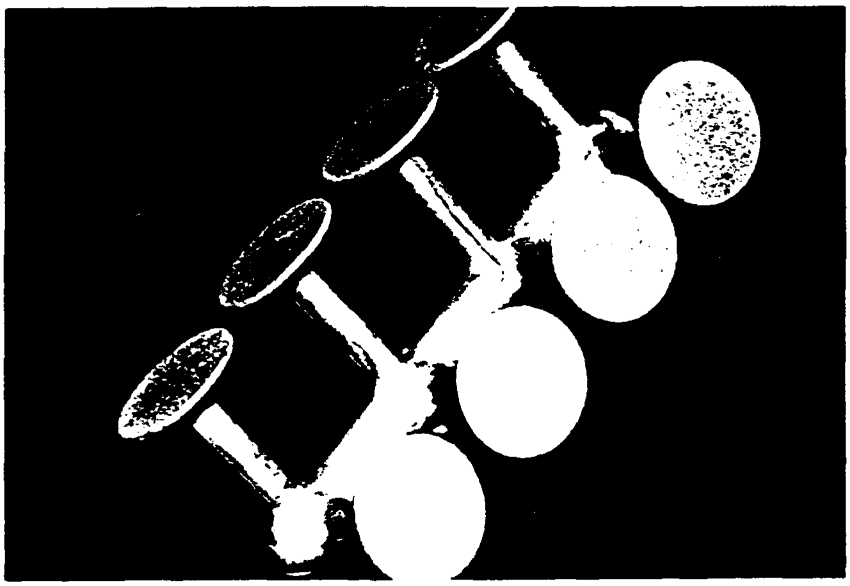

Plate 3. Specimen numbers inscribed on the handle for identification.

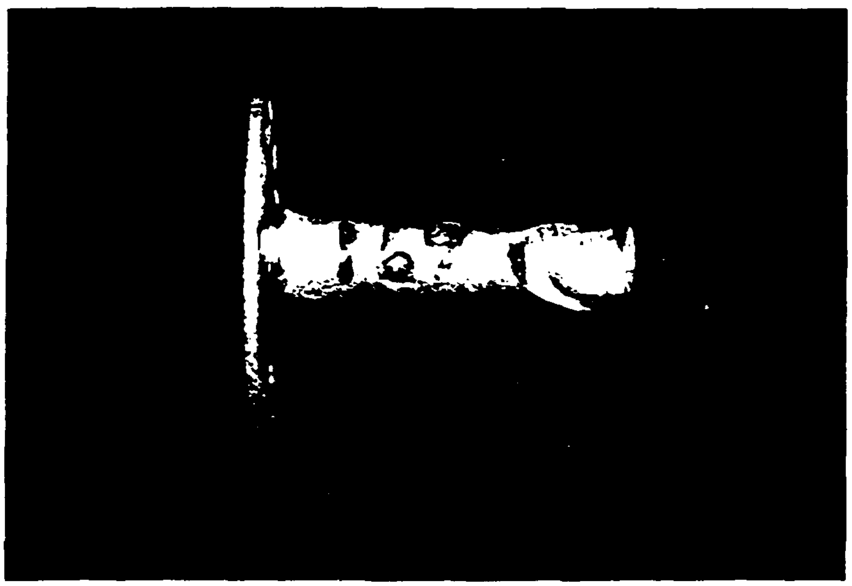

Plate 4. Four depressions on the undersurface of the metal substructures served as thickness measurement indices.

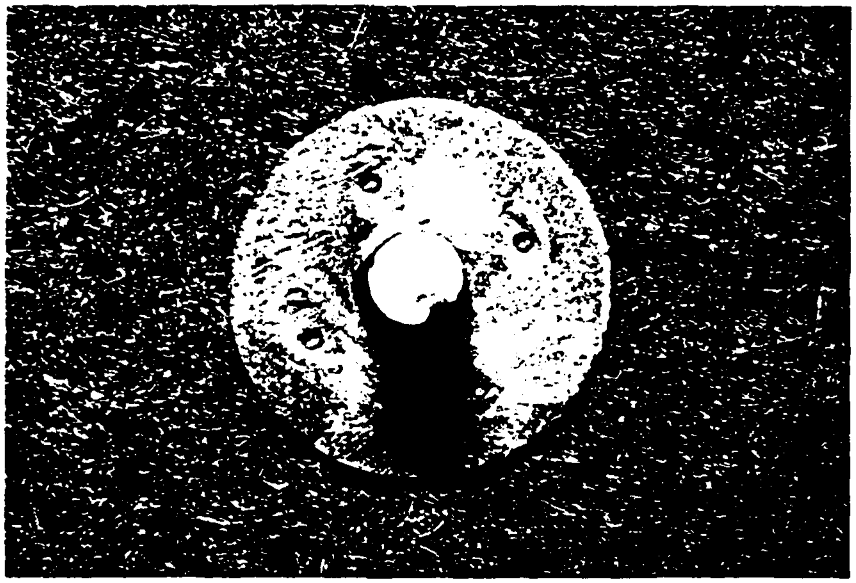

Plate 5. Angled notch on sprue of metal substructure to aid engagement of ligature wire used to hold the specimen in the custom shade tab former.

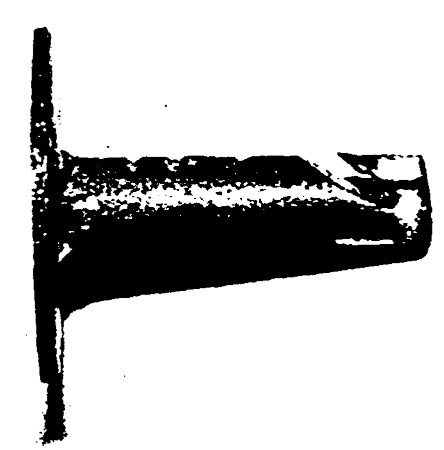

Plate 6. Representative examples of metal substructures oxidized in groups of six.

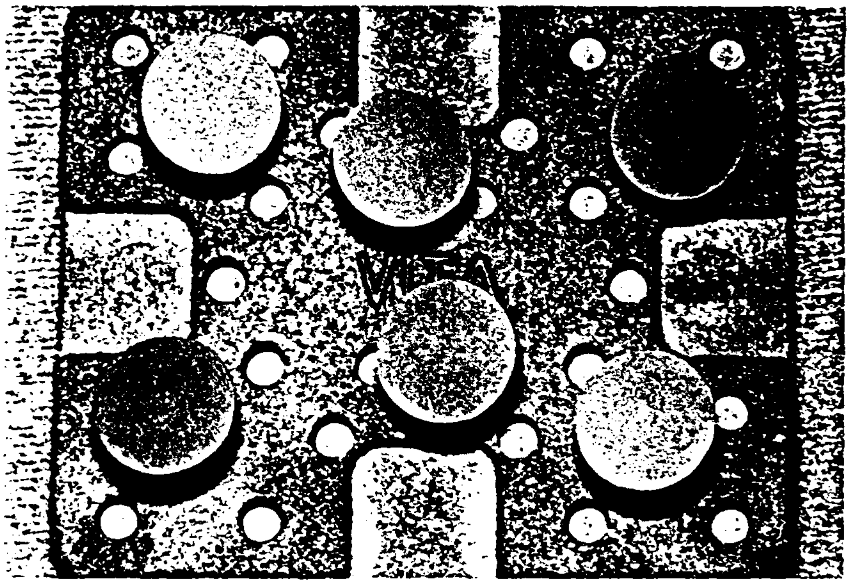

Plate 7. Hole placed through center of the custom shade tab device to accommodate ligature wire and the handle of the specimen.

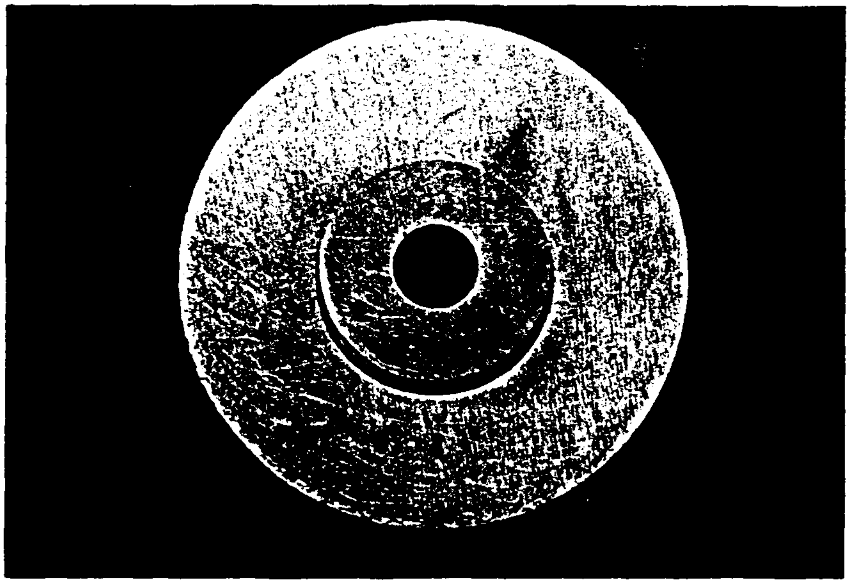

Plate 8. Measurement scale on the sides of the Belle de St. Claire custom shade tab device.

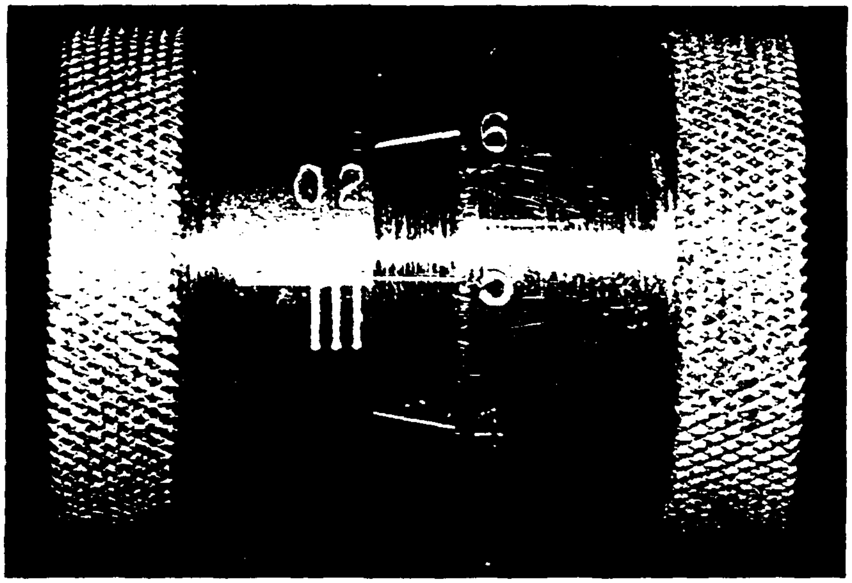
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Plate 9. Ligature wire used to hold the metal substructures securely in the custom shade tab device. The other end of the ligature wire was wrapped around the investigator's ring finger.

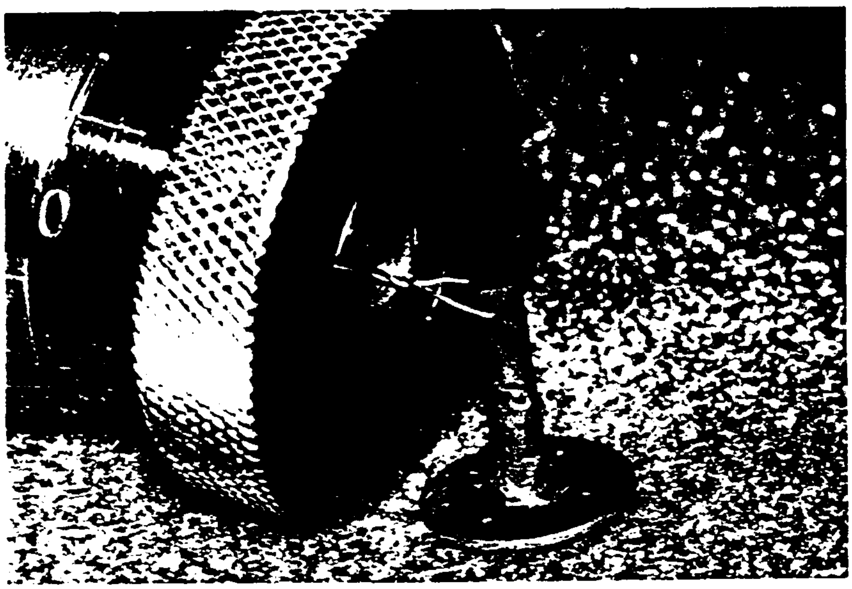

Plate 10. Porcelain placed in the custom shade tab device with a No. 4 porcelain brush.

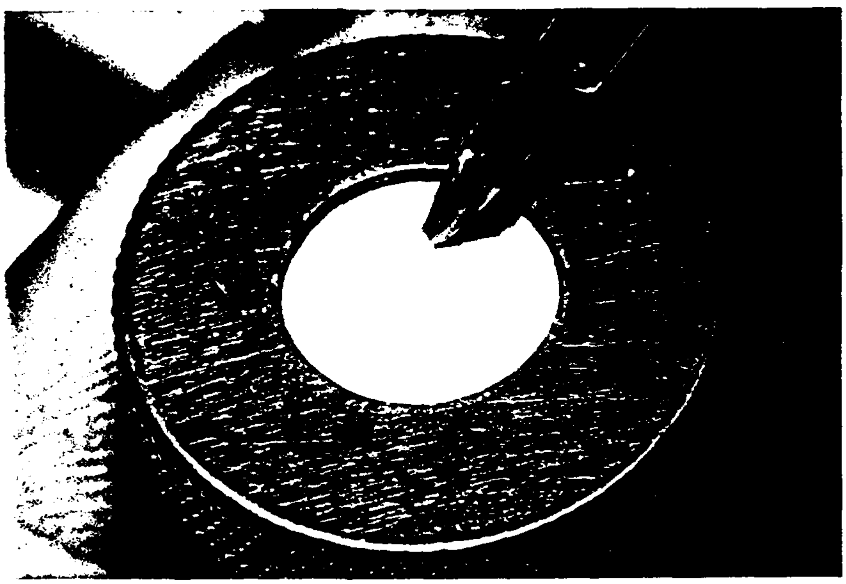

Plate 11. Porcelain surface smoothed with a dry, sable brush.

Plate 12. Dial caliper used to measure specimen thickness.

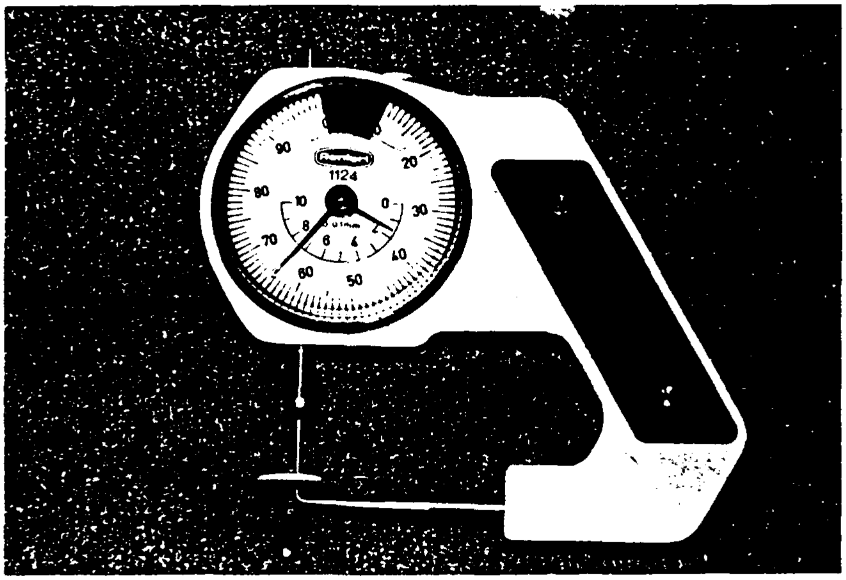
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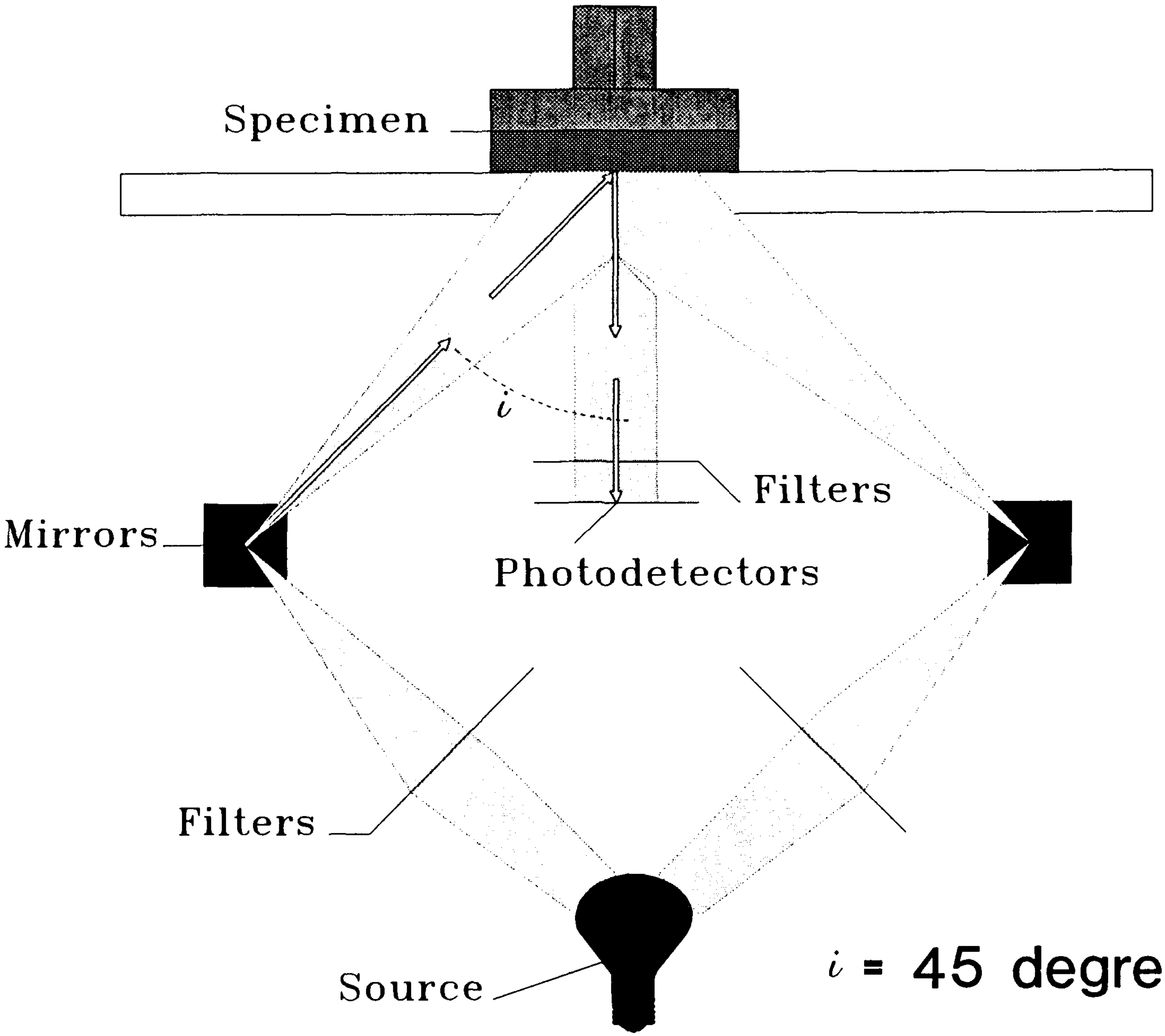
Plate 13. HunterLab Colorimeter D25A-2 Optical Geometry (HunterLab D25A-2 Colorimeter Manual, 1980).


Specimen
Mirrors
Filters
Photodetectors
Filters
Source
i

i = 45 degrees

Plate 14. Specimens mounted in random arrangement on a neutral gray mat panel for subjective observer analysis.

IV. Results

All raw tristimulus color data are contained in Appendix C. The means and standard deviations of the L*, a*, and b* color data for each porcelain brand are listed in Tables 1, 2, 3, and 4. The results of the three-factor analysis of variance ($p<0.05$) for L*, a*, and b* means are presented in Tables 5, 6, and 7, respectively. The results of the Tukey's Studentized Range Test ($p<0.05$) for L*, a*, and b* means between thicknesses of each brand-shade combination are presented in Tables 8, 9, and 10 respectively. Graphic representations of L* changes in thickness of dentin porcelain for shades A3.5, B1, and C3 are illustrated in Figures 1, 2, and 3 respectively. Graphic representations of a* changes by thickness of dentin porcelain for shades A3.5, B1, and C3 are illustrated in Figures 4, 5, and 6, respectively and b* in Figures 7, 8, and 9, respectively.

A. L*a*b* Analysis

The results of the three-factor analysis of variance for L*, a*, and b* demonstrated significant differences between brands, thicknesses, and shades of dental porcelain at the $p<0.05$ level (Tables 5, 6, and 7).

1. L* Comparisons Within Brand-Shade Groups

Upon comparing the L* means for value differences (Table 8), significant differences were noted between all thicknesses of all three shades for Microbond, Jelenko, and Vita VMK 68 porcelains but only shade B1 for Ceramco II porcelain. However, for Ceramco II shade A3.5 there were no significant differences between the 0.3 and 0.6 mm thickness groups or between the 0.6 and 0.9 mm thickness groups. But the L* value difference between the 0.3 and the 0.9 mm thicknesses were statistically significant. Also, for Ceramco II porcelain shade C3 there were no significant differences for L* values among the 0.3, 0.6, and 0.9 mm thickness groups.

2. a* Comparisons Within Brand-Shade Groups

When comparing the a* means (Table 9), significant differences were noted between all thicknesses of shade A3.5 for both Ceramco II and Jelenko porcelains. The remaining brand-shade combinations can be characterized as follows: 1) for Microbond shade A3.5 there were no significant differences between opaque only and the 0.3 mm dentin porcelain thickness and between 0.3, 0.6, and 0.9 mm dentin porcelain thickness. 2) for Microbond shade B1 there were no significant differences between opaque only and the 0.3 mm dentin thickness and also between 0.6 and 0.9 mm dentin porcelain thickness. 3) for Microbond shade C3 there were no significant differences between 0.3, 0.6, and 0.9 mm dentin porcelain

thicknesses. 4) for Ceramco II shade B1 there were no significant differences between opaque only and the 0.3 mm thickness or between the 0.3, 0.6, and 0.9 mm dentin porcelain thicknesses. 5) for Ceramco II shade C3 there were no significant differences between the 0.6 and the 0.9 mm dentin porcelain thicknesses. 6) for Jelenko shade B1 there were no significant differences between the 0.6 and the 0.9 mm of dentin porcelain thicknesses. 7) for Jelenko shade C3 there were no significant differences between the 0.3, 0.6, and 0.9 mm dentin porcelain thicknesses. 8) for Vita VMK 68 shades A3.5 and B1 there were no significant differences between the 0.6 and 0.9 mm dentin porcelain thicknesses. 9) for Vita VMK 68 shade C3 there were no significant differences between opaque only, the 0.6, and 0.9 mm dentin porcelain thicknesses.

3. b* Comparisons Within Brand-Shade Groups

Upon comparing the b* means (Table 10), significant differences were noted between all thicknesses of Jelenko shades A3.5 and B1. The remaining brand-shade combinations can be characterized as follows: 1) for Microbond shade A3.5 there were no significant differences between the 0.3, 0.6, and 0.9 mm dentin porcelain thicknesses. 2) for Microbond shade B1 there were no significant differences between the opaque only, the 0.3, and 0.9 mm and between the 0.3 and 0.6 mm dentin porcelain thicknesses. 3) for Microbond shade C3 there were also no significant differences between the opaque only, the 0.3, and 0.9 mm and between the 0.3

and 0.6 mm dentin porcelain thicknesses. 4) for all three shades of Ceramco II there were no significant differences between the opaque only and the 0.3 mm dentin porcelain thicknesses. 5) for Jelenko shade C3 there were no significant differences between the opaque only and the 0.6 mm dentin porcelain thickness. 6) for Vita VMK 68 shade A3.5 there were no significant differences between the 0.3 and 0.9 mm dentin porcelain thicknesses. 7) for Vita VMK 68 shade B1 there were no significant differences between the opaque only and the 0.6 mm of dentin porcelain thickness. 8) for Vita VMK 68 shade C3 there were no significant differences between the 0.3 and 0.6 mm dentin porcelain thicknesses mean b* value.

B. Subjective Observer Analysis

The raw data for subjective observer rankings for each brand-thickness-shade representative specimen are listed in Appendix D.

1. Interobserver Reliability

The results of interobserver reliability analysis with the alpha coefficient test appear in Table 11. This test first determines multiple pairwise correlation coefficients for each possible pairing of subjective observers. A correlation matrix of these pairwise comparisons (between observers) appears as item A in Table 11. One rater (EI) had low correlation coefficients (five out of six coefficients below 0.4) while the remaining six raters had

correlation coefficients ranging from 0.429 to 0.739. The alpha coefficient for overall interobserver correlation was found to be 0.845. For comparative purposes, alpha coefficients were also calculated for the data with each individual observer's ratings omitted from the analysis (Table 11, B).

2. Mean Rank Analysis

The summary of the Kruskal-Wallis one-way analysis of variance for thickness (using mean subjective observer ranking) is presented in Table 12. Significant differences ($p<0.05$) were noted for all brands of shade A3.5 and for Microbond and Ceramco II shade C3. To further delineate these differences a post-hoc test for non-parametric data, the Mann-Whitney Rank Sum Test, was completed between thicknesses for each brand-shade combination. The results for shades A3.5, B1, and C3 are included in Tables 13, 14, and 15, respectively.

3. Shade A3.5 Mean Rank Analysis Within Brand-Shade

For shade A3.5, there were no significant differences in ranking between different thicknesses of Microbond porcelain (Table 13). For Ceramco II mean rankings, there were no significant differences noted between the opaque only and the 0.9 mm and between the 0.3, 0.6, and 0.9 mm dentin porcelain thicknesses. For Jelenko, no significant differences were noted between the opaque

only, the 0.3, and 0.6 mm and between the opaque only, the 0.6, and 0.9 mm dentin porcelain thicknesses. For Vita VMK 68 there were no significant differences between the 0.3, 0.6, and 0.9 mm of dentin porcelain thicknesses.

4. Shade B1 Mean Rank Analysis Within Brand-Shade

Mean rankings for shade B1 were not significantly different between the four thicknesses of each brand-shade group (Table 14).

5. Shade C3 Mean Rank Analysis Within Brand-Shade

Mean rankings for shade C3 were not significantly different between the four thicknesses of dentin porcelain (0.0, 0.3, 0.6, and 0.9) for Jelenko and Vita VMK 68 porcelains (Table 15). For Microbond, no significant differences were noted in mean rank between the opaque only, the 0.3, and 0.6 mm dentin porcelain. For Ceramco II, no significant differences in mean rank were noted between the opaque only and the 0.3 mm, between the 0.6 and 0.9 mm, and between the 0.3 and 0.9 mm dentin porcelain thicknesses.

6. Mean Rank Analysis Between Brands Within Shade

Based on the analysis between thicknesses within each brand-shade group, a specimen was chosen that had the thinnest dentin porcelain which had no significant differences in mean rank with

the specimen that had the highest mean rank for that brand-shade combination. These specimens were compared to one another within each shade group between brands. The Kruskal-Wallis one-way analysis of variance between brands within shades is summarized in Table 16. Significant differences ($p < 0.05$) were noted for shades B1 and C3 but not for Shade A3.5.

A summary of the Mann-Whitney Rank Sum Tests between brands within shades is listed in Table 17. The only significant difference in mean rank for shade B1 was between Microbond and Jelenko porcelains. The only significant difference in mean rank for shade C3 was between Ceramco II and Jelenko porcelains.

Table 1. Mean (Standard Deviation) L*a*b* Values

For Microbond

SHADE A3.5				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	77.14 (0.36)	69.18 (0.36)	64.34 (0.46)	61.28 (0.20)
a*	4.26 (0.68)	3.87 (0.16)	3.51 (0.19)	3.40 (0.28)
b*	18.71 (0.62)	22.65 (0.54)	23.63 (0.45)	23.52 (0.60)

SHADE B1				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	83.22 (0.22)	76.21 (0.54)	71.98 (0.27)	68.93 (0.15)
a*	1.60 (0.12)	1.47 (1.09)	0.46 (0.02)	0.06 (0.18)
b*	14.86 (0.28)	15.59 (0.29)	15.78 ([illegible].28)	15.22 (0.26)

SHADE C3				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	73.17 (0.24)	66.42 (0.29)	63.04 (0.29)	60.47 (0.29)
a*	1.69 (0.18)	1.35 (0.02)	1.23 (0.14)	1.34 (0.16)
b*	18.45 (0.32)	18.82 (0.55)	19.21 (0.30)	18.27 (0.44)

Table 2. Mean (Standard Deviation) L*a*b* Values For Ceramco II

SHADE A3.5				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	70.56 (0.22)	66.60 (0.22)	65.64 (0.72)	64.78 (1.67)
a*	4.42 (0.16)	3.35 (0.21)	2.39 (0.13)	1.68 (0.20)
b*	22.86 (0.15)	22.50 (0.35)	19.45 (0.38)	17.62 (0.67)

SHADE B1				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	77.00 (0.46)	71.95 (0.24)	69.88 (0.80)	67.65 (0.24)
a*	-0.11 (0.19)	-0.33 (0.16)	-0.43 (0.14)	-0.38 (0.18)
b*	14.24 (0.14)	14.11 (0.16)	11.76 (0.32)	10.29 (0.19)

SHADE C3				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	68.32 (0.08)	65.26 (0.59)	64.32 (0.92)	63.66 (1.72)
a*	2.67 (0.24)	1.97 (0.23)	1.36 (0.16)	1.04 (0.35)
b*	19.63 (0.25)	19.62 (0.70)	16.87 (0.45)	15.62 (0.31)

Table 3. Mean (Standard Deviation) L*a*b* Values For Jelenko

SHADE A3.5				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	70.80 (0.46)	66.79 (0.18)	64.78 (0.32)	63.34 (0.42)
a*	4.41 (0.25)	3.51 (0.18)	2.99 (0.00)	2.56 (0.14)
b*	24.90 (0.34)	25.62 (0.36)	23.54 (0.30)	21.83 (0.46)

SHADE B1				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	78.99 (0.04)	75.13 (0.23)	71.88 (0.21)	69.38 (0.19)
a*	-0.02 (0.19)	-0.51 (0.16)	-0.79 (0.14)	-0.85 (0.17)
b*	14.45 (0.28)	13.77 (0.41)	12.44 (0.21)	11.20 (0.25)

SHADE C3				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	67.92 (0.36)	64.54 (0.26)	62.13 (0.41)	60.71 (0.64)
a*	1.75 (0.02)	0.96 (0.13)	0.87 (0.19)	0.97 (0.17)
b*	17.96 (0.38)	19.22 (0.34)	17.83 (0.50)	16.68 (0.58)

Table 4. Mean (Standard Deviation) L*a*b* Values For Vita VMK 68

SHADE A3.5				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	75.16 (0.32)	68.59 (0.56)	64.86 (0.20)	62.65 (0.19)
a*	1.28 (0.83)	2.10 (0.18)	2.82 (0.19)	3.09 (0.19)
b*	17.86 (0.45)	23.84 (0.33)	24.53 (0.27)	23.92 (0.11)

SHADE B1				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	78.56 (0.48)	74.92 (0.22)	72.20 (0.28)	70.42 (0.20)
a*	1.01 (0.13)	0.49 (0.14)	0.23 (0.12)	0.13 (0.15)
b*	13.20 (0.48)	13.91 (0.13)	13.27 (0.09)	12.48 (0.12)

SHADE C3				
Dentin Porc.	0.0 mm	0.3 mm	0.6 mm	0.9 mm
L*	74.38 (0.36)	67.81 (0.36)	64.23 (0.24)	61.78 (0.22)
a*	1.01 (0.13)	0.67 (0.17)	0.94 (0.14)	1.10 (0.01)
b*	17.34 (0.27)	20.40 (0.18)	20.33 (0.13)	19.00 (0.16)

TABLE 5. SUMMARY TABLE FOR THREE FACTOR ANALYSIS OF VARIANCE OF L*

SOURCE OF VARIATION	SS	DF	MS	F	Sig of F
Main Effects	7782.925	8	972.866	3751.804	.000
Brand	190.057	3	63.352	244.315	.000
Thickness	4078.926	3	1359.642	5243.386	.000
Shade	3513.941	2	1756.970	6775.661	.000
2 Way Interactions	510.466	21	24.308	93.742	.000
Brand-Thick	365.070	9	40.563	156.430	.000
Brand-Shade	129.987	6	21.664	83.548	.000
Thick-Shade	15.409	6	2.568	9.904	.000
3 Way Interactions					
Brand-Thick-Shade	102.904	18	5.717	22.047	.000
Explained	8396.295	47	178.645	688.933	.000
Residual	62.233	240	.259		
Total	8458.529	287	29.472		

TABLE 6. SUMMARY TABLE FOR THREE FACTOR ANALYSIS OF VARIANCE OF a*

SOURCE OF VARIATION	SS	DF	MS	F	Sig of F
Main Effects	480.361	8	60.045	792.025	.000
Brand	26.238	3	8.746	115.365	.000
Thickness	28.306	3	9.435	124.457	.000
Shade	425.817	2	212.909	2808.367	.000
2 Way Interactions	63.893	21	3.043	40.133	.000
Brand-Thick	22.117	9	2.457	32.414	.000
Brand-Shade	40.359	6	6.726	88.726	.000
Thick-Shade	1.418	6	.236	3.117	.006
3 Way Interactions					
Brand-Thick-Shade	29.189	18	1.622	21.39	.000
Explained	573.444	47	12.201	160.936	.000
Residual	18.195	240	.076		
Total	591.639	287	2.061		

TABLE 7. SUMMARY TABLE FOR THREE FACTOR ANALYSIS OF VARIANCE OF b*

SOURCE OF VARIATION	SS	DF	MS	F	Sig of F
Main Effects	3983.932	8	497.991	3639.516	.000
Brand	114.537	3	38.179	279.027	.000
Thickness	154.194	3	51.398	375.636	.000
Shade	3715.201	2	1857.600	13576.070	.000
2 Way Interactions	589.702	21	28.057	205.053	.000
Brand-Thick	366.614	9	40.735	297.706	.000
Brand-Shade	165.229	6	27.538	201.260	.000
Thick-Shade	57.359	6	9.560	69.867	.000
3 Way Interactions					
Brand-Thick-Shade	104.779	18	5.821	42.543	.000
Explained	4677.912	47	99.530	727.405	.000
Residual	32.839	240	.137		
Total	4710.751	287	16.414		

Table 8. Tukey's Studentized Range Test
For L*

Thickness (mm)	Microbond	Ceramco II	Jelenko	Vita VMK 68
	Shade A3.5			
0.0	77.14	70.56	70.80	75.16
0.3	69.18	66.60	66.79	68.59
0.6	64.34	65.64	64.78	64.86
0.9	61.28	64.78	63.34	62.65
	Shade B1			
0.0	83.22	77.00	78.99	78.56
0.3	76.21	71.95	75.13	74.92
0.6	71.98	69.88	71.88	72.20
0.9	68.93	67.65	69.38	70.42
	Shade C3			
0.0	73.17	68.32	67.92	74.38
0.3	66.42	65.26	64.54	67.81
0.6	63.04	64.32	62.13	64.23
0.9	60.47	63.66	60.71	61.78

] = No Significant Differences at the p<0.05 level

Table 9. Tukey's Studentized Range Test Results
For a*

Thickness (mm)	Microbond	Ceramco II	Jelenko	Vita VMK 68
	Shade A3.5			
0.0	4.26	4.42-	4.42	1.28
0.3	3.88	3.35	3.51	2.10
0.6	3.51	2.39	3.00	2.82
0.9	3.39	1.68	2.56	3.09
	Shade B1			
0.0	1.60	-0.10	0.02	1.01
0.3	1.47	-0.30	-0.47	0.49
0.6	0.46	-0.38	-0.75-	0.23
0.9	0.06	-0.35	-0.77-	0.13
	Shade C3			
0.0	1.69	2.67	1.75	1.01
0.3	1.35	1.97	0.96-	0.67
0.6	1.22	1.36	0.87-	0.94
0.9	1.34	1.04	0.97-	1.10

] = No Significant Differences at the p<0.05 level

Table 10. Tukey's Studentized Range Test Results For b*

Thickness (mm)	Microbond	Ceramco II	Jelenko	Vita VMK 68
	Shade A3.5			
0.0	18.71	22.86	24.90	17.86
0.3	22.65	22.50	25.62	23.85
0.6	23.63	19.45	23.54	24.53
0.9	23.52	17.62	21.83	23.91
	Shade B1			
0.0	14.86	14.23	14.44	13.20
0.3	15.59	14.11	13.78	13.91
0.6	15.78	11.76	12.44	13.27
0.9	15.22	10.30	11.20	12.48
	Shade C3			
0.0	18.45	19.63	17.97	17.34
0.3	18.81	19.62	19.21	20.40
0.6	19.21	16.87	17.83	20.34
0.9	18.27	15.62	16.68	19.00

] = No Significant Differences at the $p<0.05$ level

Figure 1. Mean L* for shade A3.5 with increasing dentin porcelain thickness.

MEAN L* FOR A3.5
(L* = luminance)

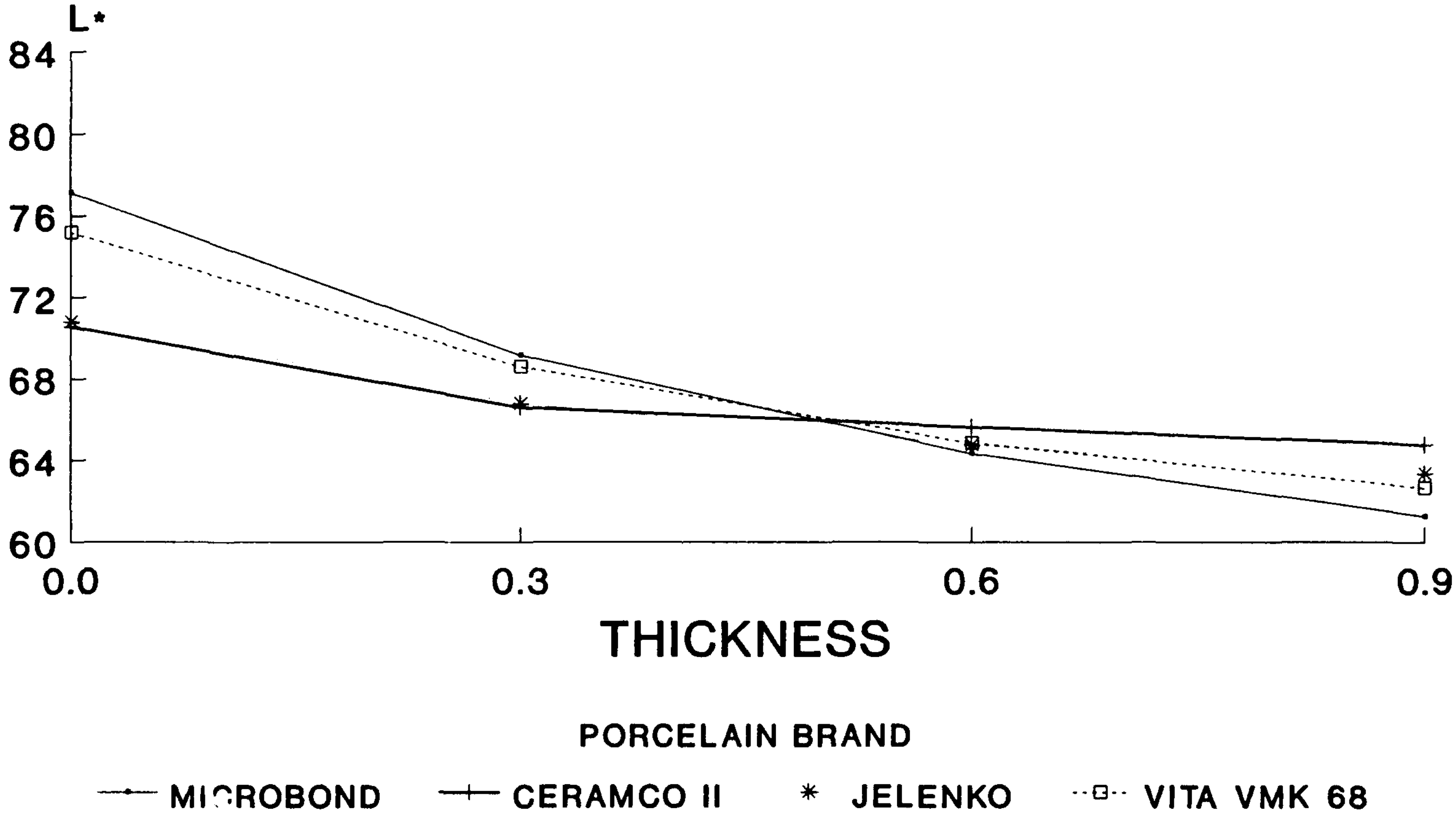


Figure 2. Mean L* for shade B1 with increasing dentin porcelain thickness.

MEAN L* FOR B1
(L* = luminance)

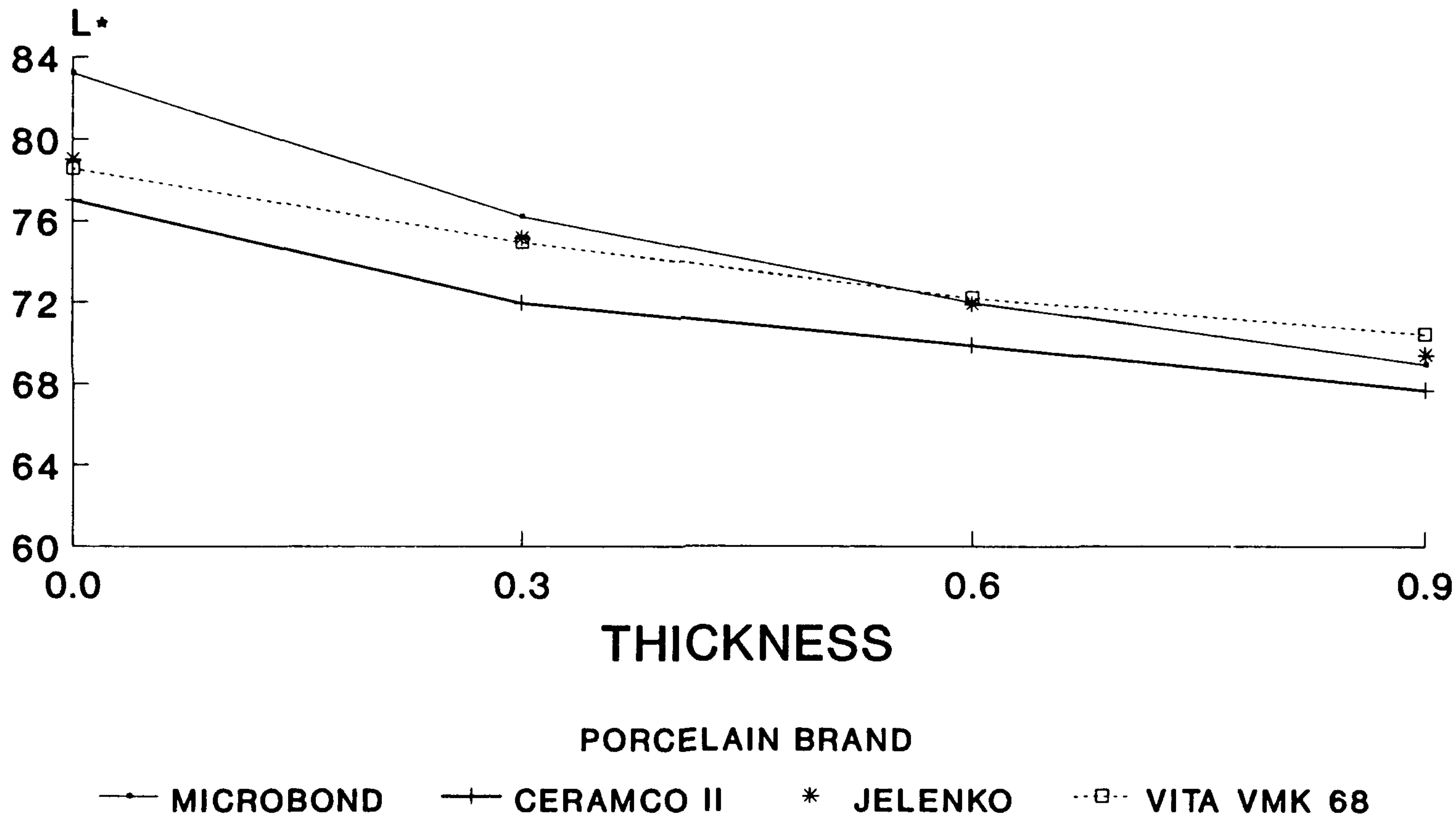


Figure 3. Mean L* for shade C3 with increasing dentin porcelain thickness.

MEAN L* FOR C3
(L* = luminance)

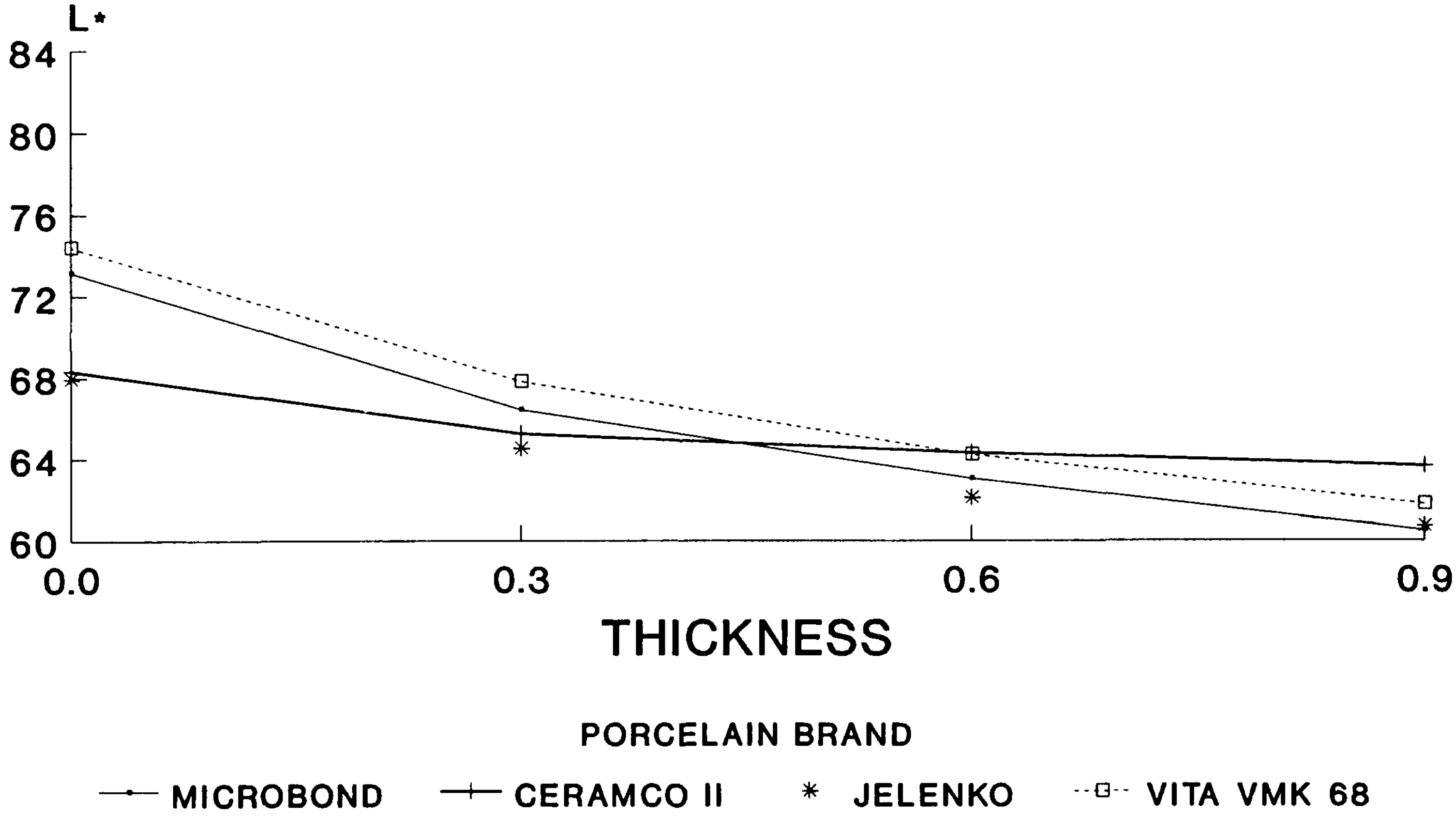


Figure 4. Mean a* for shade A3.5 with increasing dentin porcelain thickness.

MEAN a* FOR A3.5
(a* = red-green)

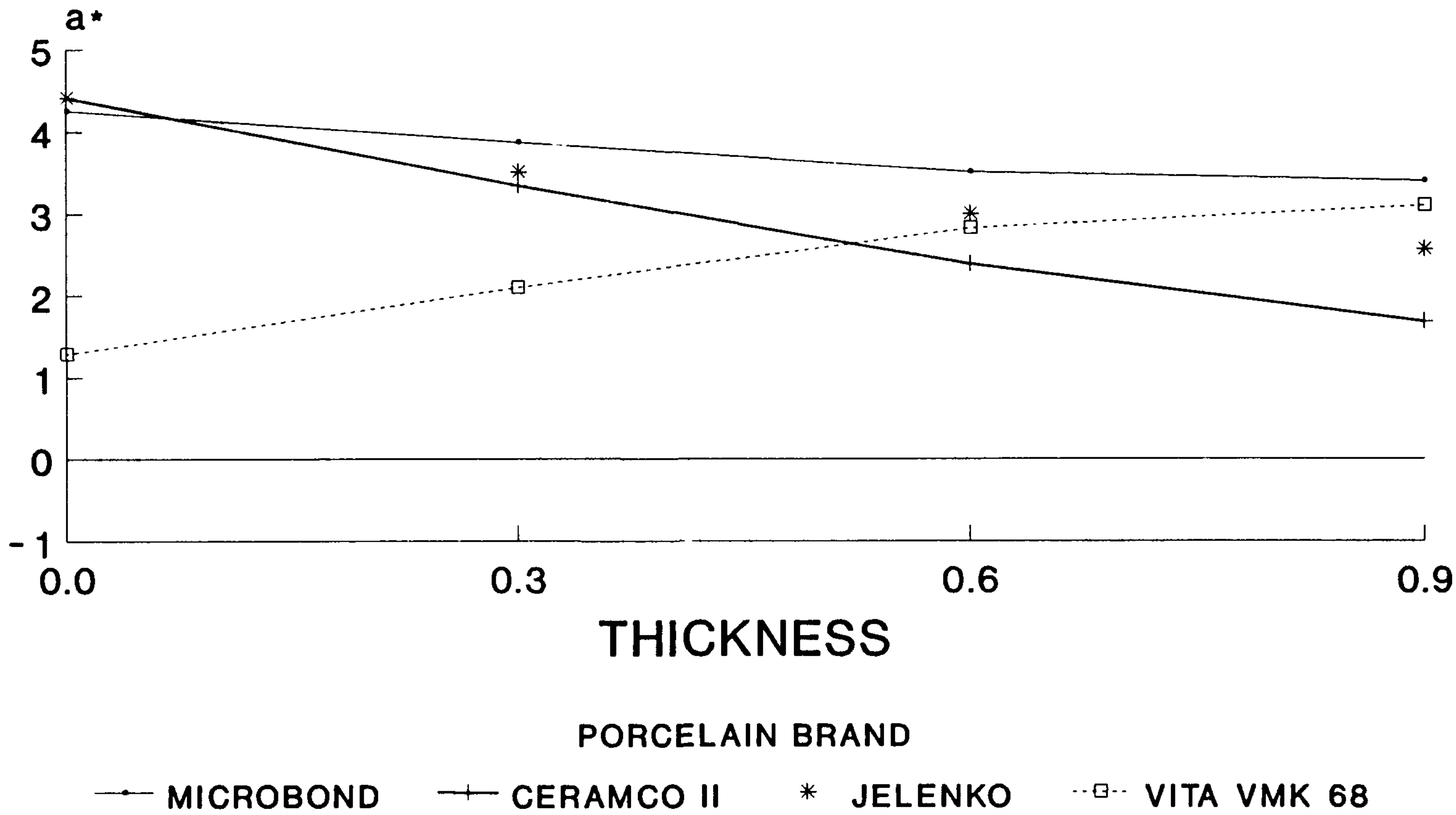


Figure 5. Mean a* for shade B1 with increasing dentin porcelain thickness.

MEAN a* FOR B1
(a* = red-green)

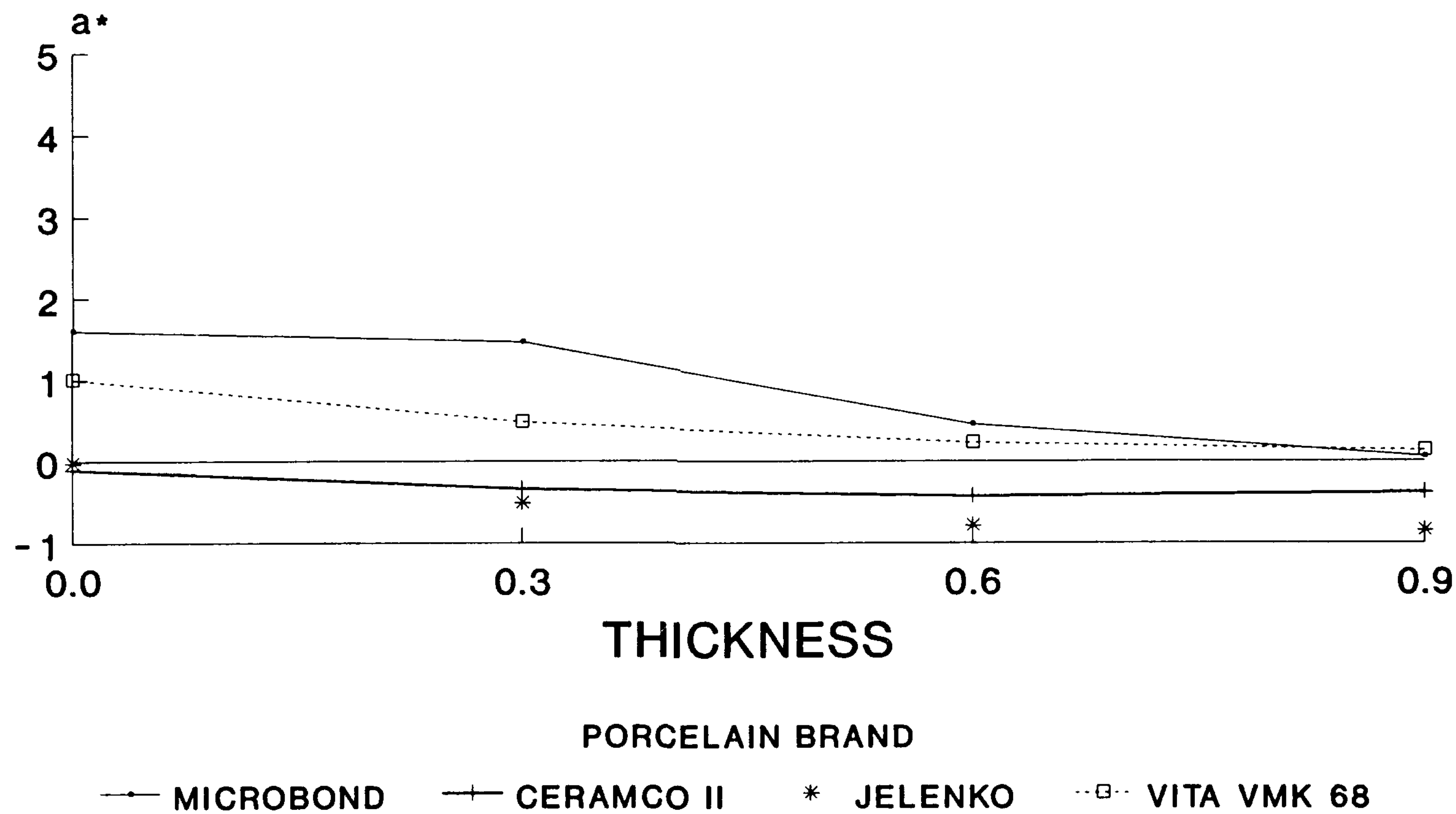


Figure 6. Mean a* for shade C3 with increasing dentin porcelain thickness.

MEAN a* FOR C3
(a* = red-green)

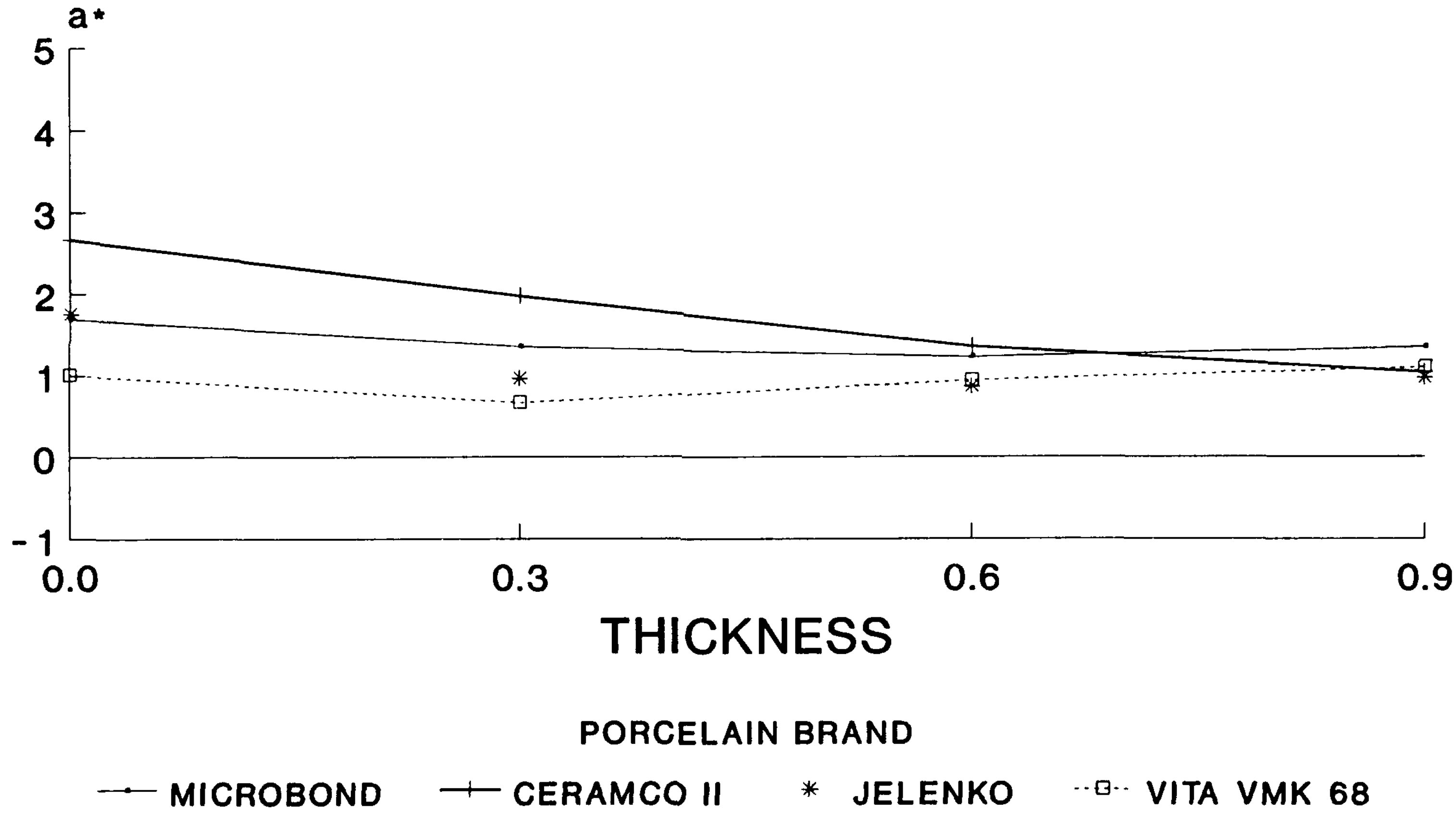


Figure 7. Mean b* for shade A3.5 with increasing dentin porcelain thickness.

MEAN b* FOR A3.5
(b* = yellow-blue)

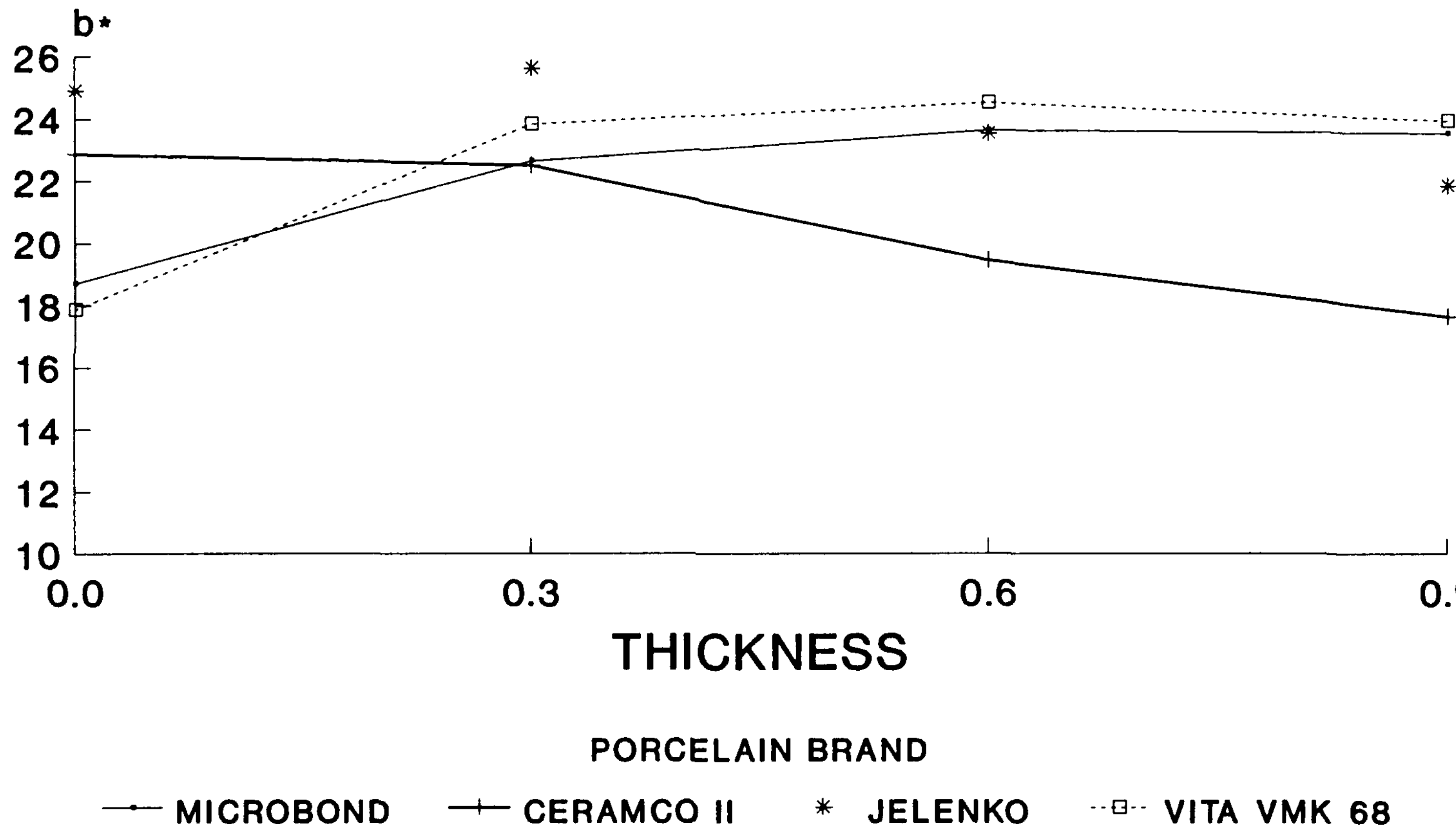


Figure 8. Mean b* for shade B1 with increasing dentin porcelain thickness.

MEAN b* FOR B1
(b* = yellow-blue)

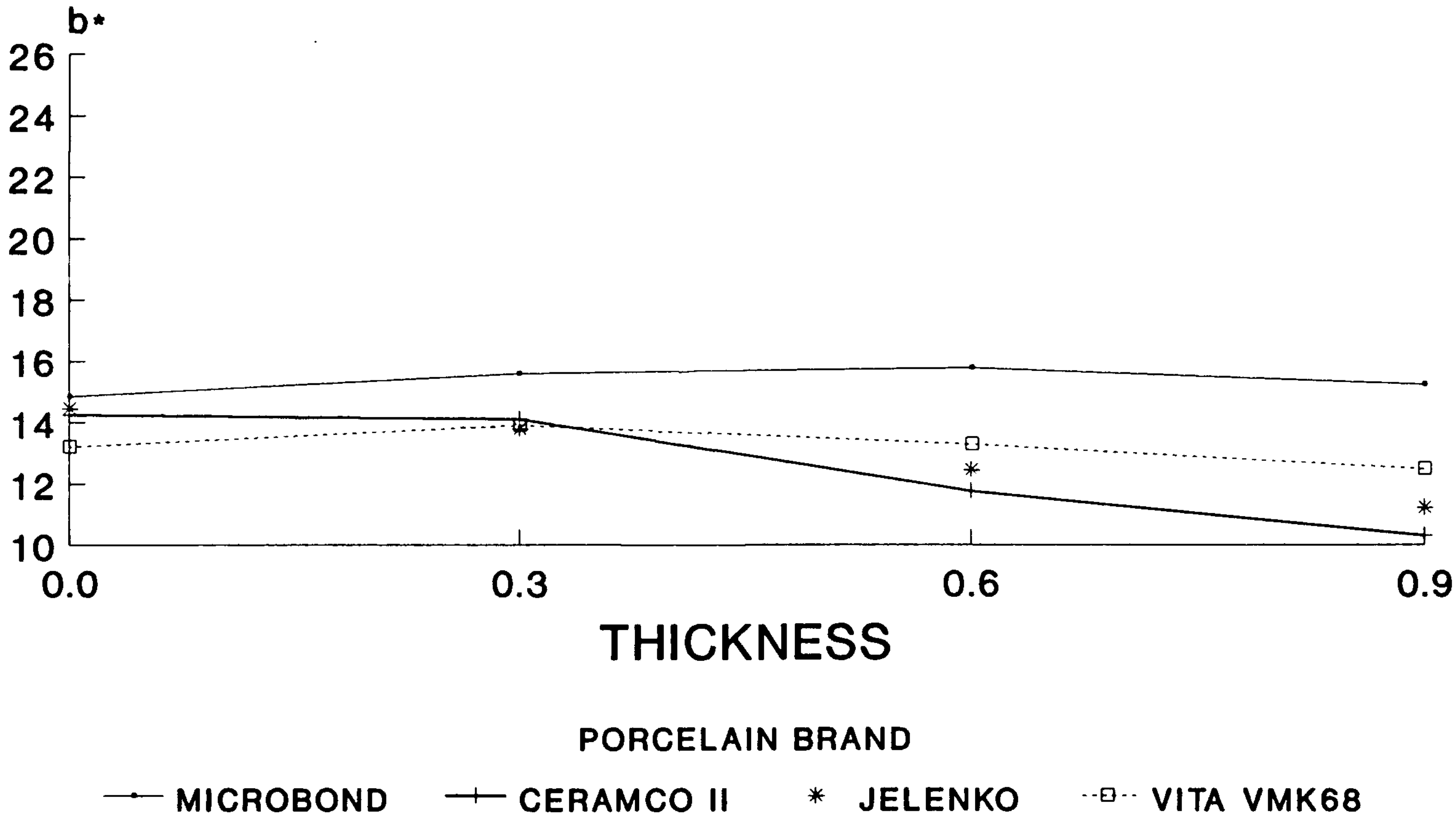


Figure 9. Mean b* for shade C3 with increasing dentin porcelain thickness.

MEAN b* FOR C3
(b* = yellow-blue)

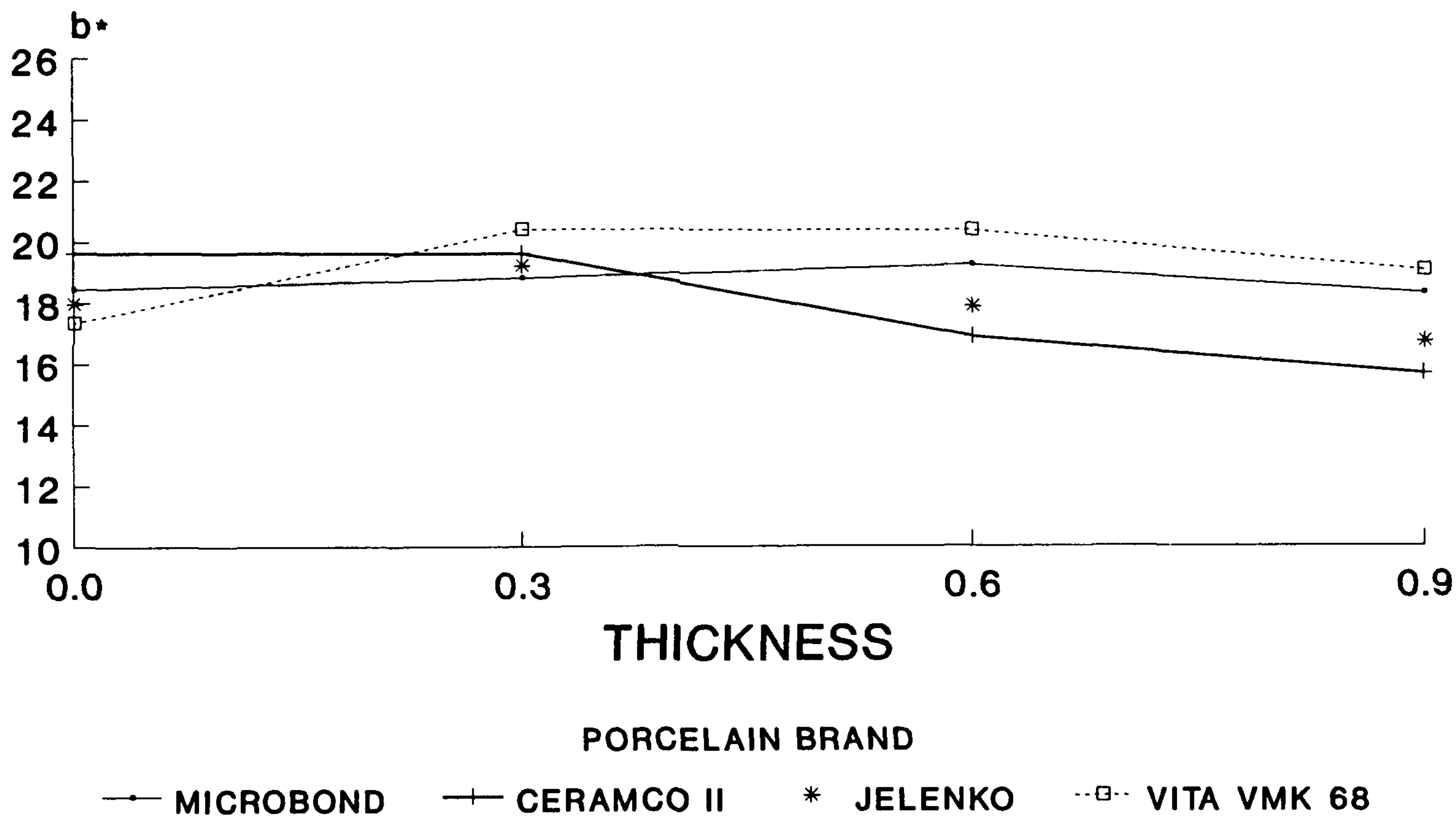


Table 11. Interobserver Reliability by Alpha Coefficient Analysis

A. Correlation Matrix

	EI	MS	RS	DR	BB	SK	JB
EI	1						
MS	.398	1					
RS	.557	.581	1				
DR	.007	.509	.436	1			
BB	.063	.586	.505	.604	1		
SK	.138	.473	.518	.594	.453	1	
JB	.044	.473	.429	.579	.739	.511	1

B. Alpha Coefficient Analysis

Rater	Corrected Rater Total Correlation	Alpha if Rater Deleted
EI	.247	.871
MS	.704	.808
RS	.706	.803
DR	.633	.815
BB	.682	.806
SK	.615	.818
JB	.645	.812

Overall Standardized Rater Alpha = 0.845

Table 12. Summary of Kruskal-Wallis One-Way Analysis of Variance Between Thickness Within Brand

Brand	Shade	K-W test	LOS *
Microbond	A3.5	8.14	0.0432 +
Ceramco II		11.57	0.0090 +
Jelenko		12.20	0.0067 +
Vita VMK 68		17.49	0.0006 +
Microbond	B1	6.19	0.1026
Ceramco II		6.90	0.0753
Jelenko		5.37	0.1467
Vita VMK 68		5.22	0.1563
Microbond	C3	15.22	0.0016 +
Ceramco II		15.29	0.0016 +
Jelenko		3.74	0.2910
Vita VMK 68		3.63	0.3045

* = Level of significance using Chi-square distribution with 3 degrees of freedom and 28 cases in each Brand-Shade group.

+ = Significant differences at the $p<0.05$ level

Table 13. Results of Mann-Whitney Rank Sum Test Between Thickness Within Brands

Shade A3.5

Brand	Thickness (mm)	Mean Rating (Standard Dev.)
Microbond	0.0	1.57 (0.78)
	0.3	3.57 (1.39)
	0.6	2.86 (1.34)
	0.9	2.00 (1.41)
Ceramco II	0.0	1.57 (0.78)
	0.3	3.57 (0.97)
	0.6	3.43 (0.97)
	0.9	2.71 (1.11)
Jelenko	0.0	3.71 (1.11)
	0.3	2.29 (0.95)
	0.6	3.29 (0.95)
	0.9	4.43 (0.53)
Vita VMK 68	0.0	1.00 (0.00)
	0.3	2.71 (1.11)
	0.6	2.29 (0.48)
	0.9	1.29 (0.48)

[= No significant differences at the Alpha< 0.05 level

Table 14. Results of Mann-Whitney Rank Sum Test Between Thickness Within Brands

Shade B1

Brand	Thickness (mm)	Mean Rating (Standard Dev.)
Microbond	0.0	2.00 (1.15)
	0.3	1.29 (0.48)
	0.6	1.00 (0.00)
	0.9	1.43 (1.13)
Ceramco II	0.0	3.14 (0.89)
	0.3	2.29 (1.11)
	0.6	3.71 (1.38)
	0.9	2.14 (1.46)
Jelenko	0.0	4.00 (0.57)
	0.3	3.00 (1.29)
	0.6	4.29 (0.95)
	0.9	3.71 (0.75)
Vita VMK 68	0.0	1.86 (0.89)
	0.3	2.29 (0.95)
	0.6	2.00 (1.00)
	0.9	1.29 (0.48)

[=No significant differences at the Alpha< 0.05 level

Table 15. Results of Mann-Whitney Rank Sum Test Between Thickness Within Brands

Shade C3

Brand	Thickness (mm)	Mean Rating (Standard Dev.)
Microbond	0.0	3.14 (1.21)
	0.3	3.29 (1.11)
	0.6	3.43 (0.53)
	0.9	1.00 (0.00)
Ceramco II	0.0	1.71 (1.11)
	0.3	1.86 (0.69)
	0.6	4.29 (0.48)
	0.9	3.86 (1.46)
Jelenko	0.0	2.29 (0.95)
	0.3	2.00 (1.29)
	0.6	3.14 (1.46)
	0.9	3.00 (1.15)
Vita VMK 68	0.0	3.29 (1.60)
	0.3	3.29 (0.95)
	0.6	3.14 (0.89)
	0.9	2.14 (1.57)

[= No significant differences at the Alpha< 0.05 level

Table 16. Summary of Kruskal-Wallis One-Way Analysis of Variance for Brand

Shade	K-W test	LOS *
A3.5	2.36	0.5017
B1	8.19	0.0422 +
C3	11.61	0.0089 +

* = Level of significance using Chi-square distribution with 3 degrees of freedom and 28 cases in each Brand-Shade group.

+ = Significant differences at the $p<0.05$ level

Table 17. Results of Mann-Whitney Rank Sum Test Between Brands Within Shade

Brand	Thickness (mm)	Shade	Mean Rating (Standard Dev.)
Microbond	0.3	A3.5	3.57 (1.39)
Ceramco II	0.3		3.57 (0.97)
Jelenko	0.6		3.29 (0.95)
Vita VMK 68	0.3		2.71 (1.11)
Microbond	0.3	B1	1.29 (0.48)
Ceramco II	0.3		2.29 (1.11)
Jelenko	0.3		3.00 (1.29)
Vita VMK 68	0.3		2.29 (0.95)
Microbond	0.3	C3	3.29 (1.11)
Ceramco II	0.6		4.29 (0.48)
Jelenko	0.3		2.00 (1.29)
Vita VMK 68	0.3		3.29 (0.95)

[= No significant differences at the Alpha< 0.05 level

V. Discussion

The control of color in dental porcelain is critical to the development of an esthetically successful restoration. Two primary methods of color analysis have been used to evaluate the color and/or shade of dental porcelain: colorimetric measurement with an instrument and subjective observer color analysis.

The HunterLab Colorimeter was used to record Y, X, and Z tristimulus values because of its simplicity, availability, and reproducibility needed for this investigation. Although spectrophotometers are considered to be a more accurate instrument for broad range color measurement, colorimeters are believed to yield comparable data for tooth color (Goodkind et al., 1985). Furthermore, instruments with different viewing geometries have been shown to give consistent results when changes in color are evaluated (Seghi, 1990).

The recorded Y, X, and Z tristimulus values were mathematically converted to L*, a*, and b* values. The CIE L*a*b* notation is the standard international color ordering system and the three dimensions (L*, a*, and b*) correlate to interpretable parameters of color (value, red-green, and blue-yellow, respectively).

Because there are no specified target L*, a*, and b* values for a particular shade of dental porcelain, interpretation of these data can be confusing and even meaningless. In an effort to lend clinical relevance to this information, subjective observers were

used in conjunction with instrumental means to analyze the specimens (Jacobs et al., 1987). The seven subjective observers were selected only after they had been tested and found to possess normal color acuity, because approximately 8% of all men and 0.4% of all women have some degree of anomalous color vision (Pau, 1988).

The L*a*b* data were used to characterize the color changes between different thicknesses of dentin porcelain while the subjective observer data were used to determine the shade matching ability of the different dentin porcelain thicknesses.

A. L* Comparisons Between Thicknesses Within Brand-Shade

1. L* For Shade A3.5

Graph analysis of change in L* values for shade A3.5 shows that Ceramco II and Jelenko porcelains have lower value opaques while Vita VMK 68 and Microbond had the higher value opaques (Figure 1 and Table 8). While the value level for Ceramco II porcelain decreased significantly between the opaque layer and the 0.3 mm dentin porcelain thickness, it remained relatively unchanged between the 0.3 and 0.6 mm dentin porcelain thicknesses. Microbond porcelain had the largest decrease in value (L*) at each thickness while the L* value for Jelenko and Vita VMK 68 porcelains decreased to a lesser extent between each successive thickness of dentin porcelain. For shade A3.5, only one of the three shade matched

opaque systems, Ceramco II, had improved L* (value) constancy with increasing dentin porcelain thickness. Furthermore, one of the shade-matched opaque systems (Microbond) had the greatest amount of L* change with increasing dentin porcelain thickness.

2. L* For Shade B1

Analysis of change in L* values for shade B1 shows that Ceramco II porcelain has lower L* means for the opaque and all other dentin porcelain thicknesses while Microbond porcelain has higher L* opaque values (Figure 2 and Table 8). Ceramco II, Jelenko, and Vita VMK 68 porcelains followed similar patterns of gradual decreases in L* means as dentin porcelain thickness is increased. However, Microbond porcelain has a larger decrease for each addition of dentin porcelain over these same B1 thicknesses. For shade B1, those porcelain systems with shade-matched opaques, as well as the non-shade-matched opaque system, lacked color constancy for L* (value) as dentin porcelain thickness increased.

3. L* For Shade C3

Analysis of change in L* values for shade C3 showed that Ceramco II and Jelenko samples again had lower opaque L* means while Microbond and Vita VMK 68 specimens had higher opaque L* means (Figure 3 and Table 8). As with shade A3.5, Ceramco II remained relatively unchanged between thicknesses of 0.3, 0.6, and

0.9 mm of dentin porcelain. Jelenko, Microbond, and Vita VMK 68 porcelains all had significant decreases in L* means as dentin porcelain became thicker. Microbond and Vita VMK 68 porcelains followed a near parallel pattern of mean L* decrease with increasing dentin porcelain thicknesses. For shade C3, only one of the shade-matched opaque porcelain systems, Ceramco II, had improved L* (value) constancy with increasing dentin porcelain thickness. Furthermore, the greatest amount of L* change occurred with one of the shade-matched opaque systems (Microbond).

4. Summary of L* Comparisons

Overall, two shades of one shade-matched opaque porcelain system, Ceramco II shades A3.5 and C3, had L* values that were unaffected by increases in dentin porcelain thicknesses past 0.3 mm. This was interpreted to mean that the addition of dentin porcelain beyond 0.3 mm would not alter the value significantly. However, all three shades of Microbond, also reported to have shade-matched opaques, consistently had the greatest decreases in L* means with increasing dentin porcelain thicknesses. All other brand-shade combinations fell in between with smaller but consistent decreases in L* means, than those of Microbond, with increasing dentin porcelain thicknesses.

The overall decrease in L* means with increasing thickness of dentin porcelain for all shades of Microbond, Jelenko, and Vita VMK 68 and shade B1 of Ceramco II metal ceramic porcelains is in

agreement with previous reports by Moser and Meyer (1983), Jacobs and others (1987), and Terada and others (1989a). On the other hand, two shades (A3.5 and C3) of the Ceramco II porcelain had decreasing L* means with increasing dentin porcelain thickness but the decreases were not statistically significant. In contrast to previous studies where L* (value) was found to decrease as dentin porcelain thickness increased, this investigation has shown that there are brand-shade combinations where L* does not significantly change as dentin porcelain thickness increases.

B. a* Comparisons Between Thicknesses Within Brand-Shade

1. a* For Shade A3.5

Graph analysis of a* (red-green) changes for shade A3.5 revealed that Vita VMK 68 began with the lowest mean a* for the opaques and steadily increased with increasing thicknesses while Microbond, Ceramco II, and Jelenko had the highest a* means and these means decreased with increasing thicknesses (Figure 4 and Table 9). Since these a* mean values were all positive they represented varying quantities of red coloration. Both Ceramco II and Jelenko porcelain samples had consistently significant decreases in a* means for each increase in dentin porcelain thickness. Microbond porcelain a* means, while decreasing slightly, were not significantly changed with increasing dentin porcelain thicknesses after the 0.3 mm level. Vita VMK 68 porcelain a* means

levelled off after 0.6 mm of dentin porcelain thickness and did not significantly change at 0.9 mm.

2. a* For Shade B1

Analysis of the a* means for shade B1 revealed that Microbond and Vita VMK 68 porcelains had low amounts of red (low +a* means) that decreased with increasing thicknesses of dentin porcelain (Figure 5 and Table 9). The a* means for Vita VMK 68 porcelain decreased between the opaque only, the 0.3, and 0.6 mm dentin porcelain thicknesses with no significant changes beyond 0.6 mm. The a* means for Microbond porcelain had a sharp decrease between the 0.3 and 0.6 mm thicknesses but were not significantly changed beyond 0.6 mm of dentin porcelain thickness. On the other hand, Ceramco II and Jelenko porcelains had low amounts of green (low -a* means) that increased with increasing dentin porcelain thickness (more negative a* values indicating an increase in green). The a* means for Ceramco II porcelain levelled off beyond the 0.3 mm thickness while Jelenko porcelain levelled off beyond the 0.6 mm dentin porcelain thickness.

3. a* For Shade C3

Analysis of a* means for shade C3 showed that all values were in the positive range indicating varying amounts of red (Figure 6 and Table 9). Ceramco II porcelain had the highest a* means and

these means significantly decreased until the 0.6 mm dentin porcelain thickness, after which there was no significant change. Vita VMK 68 porcelain had the lowest a* means that initially decreased at 0.3 mm dentin porcelain thickness then increased to levels that were not significantly different from the opaque only a* mean. Both Microbond and Jelenko porcelains levelled off at the 0.3 mm dentin porcelain thickness and had no significant changes in a* means with increasing thicknesses.

4. Summary of a* Comparison

Overall, it was clear that the red-green color changes with increasing dentin porcelain thickness were variable depending on the brand and shade.

At 0.3 mm of dentin porcelain thickness four brand-shade combinations achieved a stable a* value (redness) with no significant change at increased dentin porcelain thicknesses. All were shade-matched opaque porcelain systems. They were, Microbond shades A3.5 and C3, Ceramco II shade B1, and Jelenko shade C3. This was interpreted to indicate that the red color that is achieved with these porcelains is optimized at a dentin porcelain thickness of 0.3 mm. Consequently, there is no further advantage in increasing dentin porcelain thickness beyond 0.3 mm for this particular dimension of color.

In the same manner, at 0.6 mm of dentin porcelain thickness six brand-shade combinations achieved a stable a* value (redness).

Three used non-shade-matched opaque (Vita VMK 68 shades A3.5, B1, and C3), and three used shade-matched opaques (Jelenko shade B1, Ceramco II shade C3, and Microbond shade B1).

Shade A3.5 of both Ceramco II and Jelenko, both with shade-matched opaque systems, had significant changes in a* means at each increase including the 0.9 mm dentin porcelain thickness.

Red-green (a*) color constancy with increasing dentin porcelain thickness was not more likely to occur with shade-matched opaque porcelain systems than with the non-shade matched opaque system.

C. b* Comparisons Between Thickness Within Brand-Shade

Analysis of the b* data revealed that all of the values were in the positive range indicating various levels of yellow and no blue (-b*). The b* means were variable with increasing thickness depending on brand and shade.

1. b* For Shade A3.5

Graph analysis of b* (yellow) for shade A3.5 showed that Jelenko porcelain had the highest opaque only b* mean (Figure 7 and Table 10). The Jelenko b* mean significantly changed for each successive increase in dentin porcelain thickness. Vita and Microbond porcelains showed similar patterns of increasing b* with increasing thickness that levelled off beyond 0.3 mm of dentin

porcelain thickness. The b* means for Ceramco II porcelain had no significant change between the opaque only and the 0.3 mm dentin porcelain but then significantly decreased with successive increases in dentin porcelain thickness.

2. b* For Shade B1

Graph analysis of b* for shade B1 showed that Microbond porcelain had the highest means and remained relatively unchanged for all thicknesses of dentin porcelain (Figure 8 and Table 10). Ceramco II and Jelenko porcelains were similar with significant decreases in b* as dentin porcelain thickness increased. Both Microbond and Vita VMK 68 porcelains had an initial increase in b* means followed by a decrease to (Microbond) or below (Vita VMK 68) the opaque only b* mean at 0.9 mm of dentin porcelain thickness.

3. b* For Shade C3

Analysis of the b* data for shade C3 revealed that Microbond porcelain again remained relatively unchanged with increasing dentin porcelain thickness (Figure 9 and Table 10). The b* mean for Vita VMK 68 porcelain increased significantly at 0.3 mm, remained unchanged at 0.6 mm, and then decreased at 0.9 mm of dentin porcelain thickness. Ceramco II porcelain remained the same at 0.3 mm, then decreased at 0.6 and 0.9 mm of dentin porcelain thickness. Jelenko b* means increased significantly at 0.3 mm then decreased

at 0.6 and 0.9 mm of dentin porcelain thickness.

4. Summary of b* Comparisons

The overall b* pattern was dependent both on brand and shade of porcelain. For example, the Ceramco II b* means were statistically the same between the opaque only and 0.3 mm but then decreased (less yellow) at 0.6 and 0.9 mm of dentin porcelain thickness for all three shades.

With the exception of the opaque only and 0.3 mm thickness for shade A3.5, Microbond b* means remained relatively constant with increasing dentin porcelain thickness. This was interpreted to mean that no advantage in the yellow color space would be obtained by increasing the dentin porcelain thickness beyond 0.3 mm.

Jelenko and Ceramco II porcelains had the lowest b* means at 0.6 and 0.9 mm of dentin porcelain for all three shades (least amount of yellow).

Overall, the porcelain systems with shade-matched opaques did not have better b* (yellow) constancy with increasing dentin porcelain thickness than the non-shade-matched system.

D. Summary of L*, a*, and b* Observations

Caution should be exercised when comparing the combined L*a*b* color changes between groups. For example, between 0.3 mm and 0.6

mm of dentin porcelain thickness, Ceramco II shade A3.5 had no significant change in value (L*), a moderate decrease in red (a*) of about 1.0 unit, and a marked decrease in yellow (b*) of about 3.0 units. The greater decrease in yellow causes a shift in hue because there is now relatively more red. Since both red and yellow decreased, chroma also would be expected to decrease. The question still remains: at what proportion of red-to-yellow does the specimen match the shade tab? Furthermore, since the human eye is most sensitive to value (L*) changes, would the relatively non-significant decrease in L* be seen while the hue and chroma (a* and b*) changes remain undetected? Presently there is insufficient information to accurately relate the L*a*b* data to actual human visual perception (Kuehni and Marcus, 1979).

Nevertheless, L*a*b* data can reveal important characteristics of color change when dentin porcelain thickness is increased. For example, if all three color parameters (L*, a* and b*) were constant and did not significantly change with increasing dentin porcelain thickness, no further color advantage would be gained by increasing this thickness. This was not the case for any of the brand-shade combinations tested in this investigation. At least one of the L*a*b* parameters changed with successive increases of dentin porcelain thickness for all brand-shade combinations.

There was only one combination, Microbond shade A3.5, that had two color parameters (a* and b*) which remained the same beyond 0.3 mm of dentin porcelain thickness. Only two brand-shade combinations had two color parameters that remained constant beyond 0.6 mm of

dentin porcelain thickness, Vita VMK 68 shade A3.5 (a* and b*) and Ceramco II shade C3 (L* and a*).

Based on L*, a*, and b* changes with increasing dentin porcelain thickness, the reportedly shade-matched opaque porcelain systems do not have better color stability than the non-shade-matched system with increasing dentin porcelain thickness. Color stability was variable depending on both brand and shade of porcelain with increasing dentin porcelain thickness.

Jacobs et al. (1987) found that value decreased with increasing dentin porcelain thickness for two shades (A3 and C4) and stayed the same for one shade (B1) of Vita VMK 68 porcelain. This investigation found that all three shades (A3.5, B1, and C3) of Vita VMK 68 porcelain decreased in L* or value with increased dentin porcelain thickness. The fact that the B1 value did not change in the Jacobs et al. study but decreased in this investigation could be accounted for by the difference in opaque thickness. The 0.1 mm of opaque thickness in the Jacobs et al. study most likely had a lower value, from the influence of incompletely masking the metal substructure, than the 0.3 mm of opaque thickness in this investigation so that increased dentin porcelain thickness did not significantly change the value.

The stability of L* values beyond 0.3 mm of dentin porcelain thickness for Ceramco II shades A3.5 and C3 in this investigation is in contrast to the decreased value with increasing thickness of other investigations (Jacobs et al., 1987; Terada et al., 1989a). This points out that changes in value with increasing porcelain

thickness are dependent on shade and brand of metal ceramic porcelain.

The changes in a* (red) values in this investigation decreased or remained unchanged for all brand-shade combinations except for Vita VMK 68 shade A3.5, which had an increase in a* with increasing dentin porcelain thickness. Terada et al. (1989a) also found an increase in a* for Vita VMK 68 shade A2 at increased dentin porcelain thickness. This difference between the Vita VMK 68 shade A3.5 and the other three brands of shade A3.5 is most likely related to the remarkably low positive a* value of the Vita VMK 68 shade A3.5 opaque porcelain.

Changes in b* (yellow) with increasing dentin porcelain thickness were more variable than either L* or a* depending on brand and shade.

E. Subjective Observer Rating

The color vision evaluation of the subjective observers was designed to detect any observers with anomolous color vision so that such individuals could be excluded from the study if found. The selection of the appropriate screening tests for color vision analysis was made by the Chief, Visual Electrodiagnostic Laboratory, Brooks AFB, Texas. This individual holds a doctoral degree in ocular electrophysiology.

The PIP test is widely used to screen for congenital deficiencies in color vision. It is a relatively sensitive screen

for red-green deficiencies but does not detect blue-yellow defects (Romanchuk, 1983). Approximately 4% of individuals with red-green color vision anomalies will test normal with the PIP test. The APT 5 is also used to screen for congenital red-green color deficiencies. While approximately 5% of the individuals with red-green color anomalies will test normal with the APT 5, these persons generally are not the same as those missed by the PIP test. By combining these tests, fewer red-green color deficient individuals escape detection than when the tests are administered individually (Report of working group 41, National Academy of Sciences, 1981).

While yellow-blue color deficiencies are rare (0.002% of the population), they can be effectively identified with the FM 100 H test (Benson, 1989).

Considering the variability in human visual perception, it is not surprising that 100% interobserver reliability (alpha=1) was not attained. Culpepper (1970) found wide disagreement between dentists in shade matching the same tooth. Moreover, individual dentists could only repeat the same shade selection on different days 22% of the time.

An overall alpha coefficient of 0.8 or greater is considered an acceptable level of interrater reliability and the experimental testing procedure should be reconsidered if the alpha coefficient is 0.3 or less (Nunnally, 1967). The overall alpha coefficient for the subjective observers in this study was 0.845, indicating an acceptable level of reliability.

Correlation coefficients between 0.4 and 0.7 indicate fair interobserver reliability, while values above 0.7 signify good reliability (SPSS reference guide, 1990). Six of the observers in this study had fair (0.429) to good (0.739) interobserver reliability.

The one rater (EI) with the poorest correlation coefficients was not excluded from the analyses for three reasons. First, this rater still may represent a valid variation of human color perception. Second, the overall alpha coefficient did not dramatically improve when this rater's data was deleted (Table 11-B). And third, the alpha coefficient was still above 0.8 when this rater's data are included.

The overall mean rankings of the porcelain specimens were relatively low. As in the study by Evans (1988), very few specimens were rated as actually matching the shade tab exactly the same (5) or nearly the same (4). This finding may be due to three factors.

First, the shade tab standards were 2.2 mm thick and composed of only dentin porcelain while the test specimens were metal backed substructures with opaque and dentin porcelains. Granted, it is not ideal to be matching objects of differing composition for shade similarity, yet this is the clinical method that is used in dentistry for many practitioners (Sorensen and Torres, 1988).

Second, differences in surface texture between the shade tab and the specimens could account for the low number of the specimens that were rated as closely approximating the shade tab. By convention, opaque porcelain specimens are not polished or glazed,

so that there was a definite surface texture difference. The dentin porcelain specimens, on the other hand, were polished and glazed to match the surface texture of the shade tab as closely as possible.

Finally, a third possible reason for the poor match between the specimens and the shade tabs could be that the porcelains themselves do not accurately reproduce the shade tab colors. Based on the variability of L*, a*, and b* values for the same shade of different brands of porcelain found in this study and other reports (Seghi et al., 1986; Evans, 1988; Rosenstiel and Johnston, 1988), it is clear that different brands of porcelain of the same nominal shade do not equally match the Vita Lumin shade tabs.

1. Subjective Observer Rating of Shade A3.5

Analysis of the subjective observer rankings for shade A3.5 showed that there were not significantly better shade matches beyond 0.3 mm of dentin porcelain thickness for Microbond, Ceramco II, or Vita VMK 68 porcelains (Table 13). This finding was interpreted to mean that the best shade match with these porcelains was obtained at this thickness and that additional thickness of A3.5 dentin porcelain did not contribute to improved shade matching. While the highest mean rank for Jelenko shade A3.5 (4.43 ± 0.53) was obtained at 0.9 mm of dentin porcelain thickness, this was not significantly different from the 0.6 mm mean rank. Therefore additional thickness of dentin porcelain beyond 0.6 mm did not significantly improve the shade match for Jelenko A3.5.

Overall, the Jelenko A3.5 porcelain had the highest rating or best shade match for opaque only (3.71 ± 1.11) and 0.9 mm (4.43 ± 0.53) of dentin porcelain. The Vita VMK 68 opaque had the lowest rank (1.00 ± 0.00) or poorest shade match with all seven observers ranking it "not at all the same." The specimens with the thinnest dentin porcelain thickness beyond which no improvement in mean rank was observed were selected for each brand of shade A3.5 (0.3 mm of dentin porcelain for Microbond, Ceramco II, and Vita VMK 68 porcelains, and 0.6 mm of dentin porcelain for Jelenko). Comparison revealed no significant differences in shade matching between these specimens (Tables 16 and 17).

2. Subjective Observer Rating of Shade B1

Analysis of the mean rank data for all four brands of shade B1 revealed that no significant differences in shade match existed between thicknesses of dentin porcelain (Table 14). This outcome was interpreted to mean that dentin porcelain thicknesses beyond 0.3 mm did not improve shade match with the B1 shade tab for any of the four evaluated porcelains.

The fact that subjective observers could not discriminate between different thicknesses of shade B1 is consistent with the results of Jacobs and others (1987). This difficulty with discrimination of shade B1 occurred for all four brands of porcelain. Jacobs and others interpreted this to mean that when the opaque porcelain shade more closely matched the dentin porcelain

shade, a shade match would be achieved at thinner dentin porcelain thicknesses. However, analyses of the L*, a*, and b* means in this study with increasing thicknesses of dentin porcelain do not support this contention.

L* means (value) were high and, though they decreased with increasing dentin porcelain thicknesses for shade B1, they remained high in comparison to shades A3.5 and C3. There were significant changes for a* (red-green) and b*(yellow) for some brands of shade B1, however these absolute values were at low chroma levels. It is more likely that this low chroma is very near or below the threshold detection level for visual receptors and, consequently, color changes at this level are not readily discernible.

Of all of the shade B1 mean subjective rankings, Jelenko had the highest rating (4.29 ± 0.95) at 0.6 mm while Microbond had the lowest rating (1.00 ± 0.00) at 0.6 mm of dentin porcelain thickness. Jelenko had consistently higher mean rankings at all thicknesses of dentin porcelain for shade B1. Improvement in shade matching ability was not observed beyond 0.3 mm of dentin porcelain thickness for shade B1 for any of the four brands evaluated. The 0.3 mm of dentin porcelain Microbond B1 specimen had a significantly lower mean rank than the 0.3 mm dentin porcelain Jelenko B1 specimen (Tables 16 and 17). This finding was interpreted to mean that the observers felt Jelenko porcelain more closely matched the shade tab.

3. Subjective Observer Rating for Shade C3

Analysis of the mean rankings for shade C3 revealed that there were no significant differences between thicknesses of Jelenko or Vita VMK 68 porcelains (Table 15). This was interpreted to mean that no significant improvement in shade match resulted from increasing the dentin porcelain thickness beyond 0.3 mm. Ceramco II mean rankings for 0.6 and 0.9 mm were significantly better than the rankings for 0.3 mm of dentin porcelain thickness. This was believed to indicate that increasing the dentin porcelain thickness beyond 0.6 mm would not significantly improve shade match. Microbond mean rankings for 0.3 and 0.6 mm were significantly better than the 0.9 mm of dentin porcelain thickness. Apparently, with this particular porcelain and shade combination, increasing the thickness of dentin porcelain beyond 0.3 mm would not significantly improve the shade match. In fact, an increase of dentin porcelain thickness to 0.9 mm actually was considered detrimental to the shade match.

The mean rank for Ceramco II at 0.6 mm of dentin porcelain thickness (4.29 ± 0.48) was the highest or best match and the mean rank for Microbond at 0.9 mm of dentin porcelain thickness (1.00 ± 0.00) was the lowest or poorest shade match. The Ceramco II 0.6 mm dentin porcelain mean rank was significantly higher than the Jelenko 0.3 mm dentin porcelain mean rank (Tables 16 and 17).

4. Summary of Subjective Observer Rating

Overall, the porcelain systems that used shade matched opaques did not achieve their best shade match at thinner dentin porcelain thicknesses than the non-shade matched opaque system. With only two exceptions, all brand-shade combinations were selected by subjective observers to have achieved a best shade match by 0.3 mm of dentin porcelain thickness. Although some brand-shade combinations received a higher rating at greater thicknesses of dentin porcelain, these combinations were usually not statistically different from the rating at 0.3 mm of dentin porcelain. One possible conclusion is that overall shade match is not influenced as much by opaque color or dentin porcelain thickness as it is by brand (ie. particular composition of the porcelain powder).

Jacobs and others (1987) found that their subjective observers had difficulty arranging specimens with 1.0 mm and specimens with 1.5 mm of dentin porcelain in order from light to dark. They concluded that a dentin porcelain thickness of 1.0 mm was of sufficient bulk to produce a good esthetic result, and it may not be necessary to use a 1.5 mm thickness. It must be pointed out, however, that these subjective observers were not comparing the specimens to a shade tab and that they were ordering them by value, not by hue or chroma.

The results of this investigation indicated that shade matching for most of the brand-shade combinations was not significantly better at thicknesses greater than 0.3 mm of dentin

porcelain. Only 17% of the brand-shade combinations (2/12), Jelenko shade A3.5 and Ceramco II shade C3, required 0.6 mm of dentin porcelain thickness to achieve the highest shade match. These findings indicated that, for the vast majority of specimens (10/12, or 83%), a 0.3 mm thickness of overlying dentin porcelain is required to achieve a closest match (for that particular porcelain) to a dentin shade tab. However, the exact thickness for some shades may be brand and shade dependent.

Generally accepted guidelines for the facial reduction of tooth structure to provide adequate space for development of esthetics in a metal ceramic restoration range from 1.2 to 1.5 mm (McLean, 1979; Yamamoto, 1985). These depths are based on the requirement of 0.3 mm of metal substructure, 0.2 mm of opaque porcelain, and a minimum of 0.7 mm of dentin porcelain (McLean, 1979). The results of this study suggest that in vivo testing is needed to determine if the minimum requirement of 0.7 mm of dentin porcelain thickness should be reconsidered. It may be that a dentin porcelain thickness of 0.3 mm may be adequate for many shades and brands of dentin porcelain.

Future studies regarding the thickness of porcelain should include clinical evaluation of variable thickness of dentin porcelain. The intraoral environment may yield different results because the background and lighting parameters dramatically differ from evaluation on a neutral gray background with controlled illumination. In addition, dentin porcelain thicknesses less than 0.3 mm should be evaluated to delineate the minimum requirements of

dentin porcelain thickness to provide clinically acceptable shade matching.

VI. SUMMARY

This investigation was designed to examine the effects of thickness and brand on the shade of dentin porcelain. Two hundred eighty-eight metal ceramic specimens were made using a custom shade tab device. Three Vita Lumin shades (A3.5, B1, and C3) of three commercially available dental porcelains that reportedly use shade-matched opaques (Microbond, Ceramco II, and Jelenko) and one commercially available dental porcelain that does not use shade-matched opaques (Vita VMK 68) were used to make six specimens in each of four thicknesses (opaque only, and 0.3, 0.6, and 0.9 mm of dentin porcelain).

Y, X and Z tristimulus values were measured using the HunterLab Colorimeter and converted to CIE L*, a*, and b* color coordinates for each specimen. Seven observers, who tested normal for color acuity, made subjective analyses of representative specimens from each brand-shade-thickness group to rate the level of shade match to a dentin porcelain shade tab. The following results and conclusions can be drawn from this investigation:

1. Significant decreases in L* (value) were noted between thicknesses within most (10/12 or 83%) of the brand-shade combinations evaluated ($p<0.05$).
2. Only two brand-shade combinations (2/12 or 17%) had few (Ceramco II shade A3.5) or no (Ceramco II shade C3) significant changes in L* (value) between thicknesses of dentin porcelain ($p<0.05$).

3. Significant differences in a* (red-green) values were noted between thicknesses depending on brand and shade ($p<0.05$).

4. Significant differences in b* (yellow-blue) values were noted between thicknesses depending on brand and shade ($p<0.05$).

5. Based on L*, a*, and b* changes, color constancy with increasing thickness of dentin porcelain was dependent on brand and shade. In addition, the porcelain systems that used shade matched opaques did not exhibit more color constancy with increasing dentin porcelain thickness.

6. The L*a*b* variability between different thicknesses of dentin porcelain suggests that manufacturers should recommend specific dimensions for thickness of dental porcelain for each shade to achieve adequate shade matching.

7. Subjective observers found that shade-matched opaques were not more likely to achieve a shade match at thinner dentin porcelain thicknesses than the system that did not have shade-matched opaques.

8. For 83% of the brand-shade combinations, the subjective observers found that 0.3 mm was considered an adequate thickness of dentin porcelain to achieve a closest match to the dentin shade tab (for that particular porcelain).

Increased thickness of dentin porcelain will not necessarily improve and, for at least one brand-shade combination, may impair shade matching.

The results of this study indicate that opaque porcelain color and thickness of dentin porcelain may not have as much effect on overall shade match as the brand of dental porcelain.

The generally held belief that 0.7 mm of dentin porcelain thickness is required to provide adequate shade matching has been called into question. Within the parameters of this study, many shades and brands of metal ceramic porcelain, 0.3 mm of dentin porcelain thickness may be adequate to provide a best shade match for a particular porcelain brand.

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Appendix A
Porcelain Firing Temperatures*

	Low Temp (°C)	Entry Time (min)	Vacuum Level (mmHg)	Vacuum Off (°C)	High Temp (°C)	Temp Rate (°C/min)	Time at Temp (min)
Microbond							
Opaque	760	5.0	None	-	977	32	0.0
Dentin	760	5.5	720	968	968	32	0.0
Glaze	760	3.0	None	-	968	32	0.5
Ceramco II							
Opaque	650	5.0	720	930	995	55	0.0
Dentin	621	5.0	720	896	918	72	0.0
Glaze	621	3.0	None	-	935	83	1.5
Jelenko							
Opaque	593	5.0	720	980	1000	56	0.0
Dentin	593	5.5	720	941	980	56	0.0
Glaze	593	3.0	None	-	980	56	1.5
Vita VMK 68							
Opaque	650	5.0	720	985	985	32	0.0
Dentin	650	5.5	720	915	915	32	0.0
Glaze	650	3.0	None	-	935	32	1.5

* The parameters of the firing schedules were provided by each porcelain manufacturer for use on the Ultramat-CDF porcelain furnace

Appendix B

Conversion Formulas

$$L^* = 24.99\,(Y^{1/3} - 0.64)$$

$$a^* = 107.72\,[(X/0.98041)^{1/3} - Y^{1/3}]$$

$$b^* = 43.09\,[Y^{1/3} - (Z/1.18103)^{1/3}]$$

Appendix C

Tristimulus Color Data

No.= Sample number; B= Brand where 1= Microbond, 2= Ceramco II, 3= Jelenko, and 4= Vita VMK 68; S= Shade where 1= A3.5, 2= B1, and 3= C3; T= Thickness of Dentin Porcelain where 1= No Dentin Porcelain, 2= 0.3 mm of Dentin Porcelain, 3= 0.6 mm of Dentin Porcelain, and 4= 0.9 mm of Dentin Porcelain.

No.	B	S	T	Y	X	Z	L*	a*	b*
1	1	1	1	52.3	52.8	43.4	77.46	3.95	17.88
2	1	1	1	51.7	52.4	42.0	77.10	4.47	18.82
3	1	1	1	51.0	51.6	42.0	76.68	4.21	18.10
4	1	1	1	52.5	52.9	42.4	77.58	3.70	19.20
5	1	1	1	51.9	52.3	41.6	77.22	3.70	19.48
6	1	1	1	51.2	52.3	41.6	76.80	5.51	18.76
7	1	2	1	62.1	61.6	55.7	82.97	1.67	14.95
8	1	2	1	62.4	61.8	55.9	83.13	1.44	15.04
9	1	2	1	62.8	62.2	56.3	83.34	1.46	15.04
10	1	2	1	62.6	62.1	56.2	83.23	1.68	14.95
11	1	2	1	63.3	62.8	57.6	83.60	1.70	14.30
12	1	2	1	62.3	61.8	56.0	83.07	1.67	14.86
13	1	3	1	45.4	45.0	36.6	73.16	1.40	18.37
14	1	3	1	44.9	44.7	35.7	72.83	1.96	18.92
15	1	3	1	45.3	45.0	36.5	73.09	1.69	18.38
16	1	3	1	46.0	45.7	37.3	73.55	1.71	18.19
17	1	3	1	45.3	45.0	36.2	73.09	1.69	18.75
18	1	3	1	45.6	45.3	37.0	73.29	1.69	18.11
19	2	1	1	41.0	41.6	29.3	70.18	4.27	22.91
20	2	1	1	41.8	42.5	30.0	70.73	4.56	22.88
21	2	1	1	41.8	42.4	30.1	70.73	4.27	22.74
22	2	1	1	41.8	42.4	30.0	70.73	4.27	22.88
23	2	1	1	41.4	42.1	29.5	70.46	4.57	23.11
24	2	1	1	41.5	42.2	29.9	70.53	4.57	22.66
25	2	2	1	51.7	50.6	46.4	77.10	-0.23	14.04
26	2	2	1	50.4	49.5	44.8	76.32	0.23	14.38
27	2	2	1	50.8	49.8	45.2	76.56	-0.01	14.38
28	2	2	1	52.3	51.2	46.9	77.46	-0.20	14.13
29	2	2	1	52.1	51.0	46.6	77.34	-0.21	14.24
30	2	2	1	51.9	50.8	46.4	77.22	-0.22	14.24
31	2	3	1	38.4	38.4	29.6	68.32	2.40	19.27
32	2	3	1	38.4	38.4	29.3	68.32	2.40	19.70
33	2	3	1	38.5	38.6	29.2	68.39	2.72	19.97
34	2	3	1	38.2	38.3	29.3	68.17	2.72	19.45
35	2	3	1	38.4	38.5	29.4	68.32	2.72	19.56
36	2	3	1	38.5	38.7	29.3	68.39	3.04	19.83
37	3	1	1	41.3	41.9	27.8	70.39	4.27	25.45
38	3	1	1	41.6	42.4	28.6	70.60	4.86	24.64
39	3	1	1	41.5	42.2	28.4	70.53	4.57	24.81
40	3	1	1	42.7	43.3	29.2	71.35	4.26	25.08
41	3	1	1	41.5	42.1	28.3	70.53	4.27	24.96
42	3	1	1	42.8	43.4	29.7	71.42	4.26	24.48
43	3	2	1	54.8	53.7	48.6	78.93	-0.07	14.91
44	3	2	1	54.9	53.8	49.3	78.98	-0.06	14.29
45	3	2	1	55.0	54.0	49.5	79.04	0.20	14.19
46	3	2	1	55.0	54.0	49.2	79.04	0.20	14.49
47	3	2	1	54.9	53.8	49.0	78.98	-0.06	14.60
48	3	2	1	54.9	53.7	49.4	78.98	-0.32	14.19
49	3	3	1	37.6	37.4	29.7	67.73	1.74	18.11
50	3	3	1	38.3	38.1	30.7	68.24	1.77	17.60
51	3	3	1	37.1	36.9	28.9	67.35	1.73	18.62
52	3	3	1	38.1	37.9	30.3	68.10	1.76	17.91
53	3	3	1	37.7	37.5	29.9	67.80	1.75	17.96
54	3	3	1	38.4	38.2	30.8	68.32	1.77	17.59
55	4	1	1	48.1	47.7	38.9	74.89	1.50	18.58
56	4	1	1	48.8	47.7	40.4	75.33	-0.40	17.59
57	4	1	1	48.8	48.5	40.1	75.33	1.79	17.93

58	4	1	1	49.2	48.8	41.0	75.58	1.53	17.33
59	4	1	1	47.8	47.5	39.0	74.70	1.76	18.14
60	4	1	1	48.5	48.1	40.1	75.14	1.51	17.61
61	4	2	1	54.3	53.6	49.7	78.64	0.93	13.29
62	4	2	1	54.9	54.3	50.7	78.98	1.20	12.89
63	4	2	1	55.1	54.4	51.2	79.10	0.96	12.60
64	4	2	1	54.2	53.5	49.8	78.58	0.92	13.09
65	4	2	1	53.6	52.9	49.0	78.23	0.90	13.29
66	4	2	1	52.9	52.3	47.6	77.82	1.13	14.02
67	4	3	1	46.5	46.0	38.4	73.87	1.16	17.42
68	4	3	1	47.5	46.9	39.6	74.51	0.92	17.11
69	4	3	1	47.2	46.6	38.9	74.32	0.91	17.60
70	4	3	1	48.1	47.5	40.1	74.89	0.95	17.18
71	4	3	1	47.6	47.0	39.2	74.57	0.92	17.68
72	4	3	1	46.9	46.4	39.1	74.13	1.18	17.03
73	1	1	2	52.4	52.9	41.9	68.90	3.67	22.15
74	1	1	2	51.1	51.7	39.7	68.61	3.67	22.98
75	1	1	2	51.6	52.2	40.2	69.54	3.98	22.39
76	1	1	2	52.1	52.6	40.9	69.26	3.98	23.06
77	1	1	2	51.1	51.7	40.0	69.40	3.98	22.00
78	1	1	2	51.6	52.2	40.7	69.40	3.98	23.31
79	1	2	2	62.7	62.3	56.6	76.38	1.04	15.47
80	1	2	2	62.4	62.0	56.5	76.25	1.03	15.58
81	1	2	2	62.6	62.0	56.0	76.74	3.69	15.55
82	1	2	2	62.6	62.1	56.3	75.20	0.97	16.00
83	1	2	2	62.8	62.2	57.3	76.13	1.03	15.15
84	1	2	2	63.2	62.6	56.7	76.56	1.05	15.78
85	1	3	2	46.6	46.4	39.3	66.75	1.37	18.15
86	1	3	2	44.8	44.6	36.3	65.91	1.32	19.38
87	1	3	2	45.2	44.9	36.2	66.60	1.36	18.62
88	1	3	2	46.0	45.7	37.0	66.29	1.34	19.59
89	1	3	2	45.4	45.1	36.8	66.45	1.35	18.51
90	1	3	2	45.2	44.9	36.3	66.52	1.36	18.64
91	2	1	2	40.7	41.4	29.1	66.52	3.35	22.61
92	2	1	2	40.8	41.4	28.9	66.21	3.34	22.55
93	2	1	2	40.6	41.2	28.7	66.60	3.35	23.05
94	2	1	2	41.3	42.0	29.9	66.83	3.35	22.04
95	2	1	2	41.8	42.5	30.2	66.67	3.67	22.56
96	2	1	2	41.8	42.4	30.1	66.75	3.02	22.22
97	2	2	2	50.1	49.1	44.3	71.62	-0.17	13.91
98	2	2	2	49.0	48.0	43.5	71.89	-0.44	14.01
99	2	2	2	52.0	51.0	46.0	72.30	-0.11	14.35
100	2	2	2	49.9	48.9	44.3	72.03	-0.43	14.13
101	2	2	2	49.7	48.7	44.0	72.10	-0.42	14.24
102	2	2	2	50.1	49.1	44.5	71.76	-0.45	14.02
103	2	3	2	38.2	38.3	29.2	65.04	2.31	19.59
104	2	3	2	38.1	38.2	29.3	66.21	2.01	18.26
105	2	3	2	38.6	38.6	29.2	65.52	1.98	20.09
106	2	3	2	38.6	38.6	29.2	65.36	1.98	20.13
107	2	3	2	38.6	38.6	29.7	64.96	1.96	19.92
108	2	3	2	38.8	38.8	29.9	64.49	1.60	19.73
109	3	1	2	42.7	43.3	29.9	67.13	3.67	25.41
110	3	1	2	41.8	42.3	28.5	66.83	3.35	25.38
111	3	1	2	41.9	42.5	29.4	66.67	3.35	25.12
112	3	1	2	42.6	43.2	29.1	66.75	3.67	25.91
113	3	1	2	42.4	43.0	28.7	66.75	3.67	25.91
114	3	1	2	42.5	43.1	29.1	66.60	3.35	25.98
115	3	2	2	55.2	54.1	49.7	75.39	-0.39	13.88
116	3	2	2	54.5	53.4	48.2	75.20	-0.68	14.43
117	3	2	2	54.0	53.0	48.3	75.01	-0.43	13.56
118	3	2	2	53.7	52.7	47.9	75.08	-0.42	14.00
119	3	2	2	54.4	53.3	49.3	74.76	-0.73	13.34
120	3	2	2	54.1	53.0	48.4	75.33	-0.40	13.44
121	3	3	2	36.9	36.7	28.8	64.96	0.93	18.67
122	3	3	2	37.5	37.4	29.3	64.49	0.90	19.57
123	3	3	2	37.7	37.6	29.5	64.57	0.90	19.23
124	3	3	2	37.3	37.1	29.2	64.57	0.90	19.08
125	3	3	2	37.7	37.5	29.8	64.49	0.90	19.57
126	3	3	2	37.2	37.1	28.8	64.16	1.23	19.17
127	4	1	2	48.0	47.7	39.0	68.10	2.08	23.92
128	4	1	2	47.9	47.6	39.0	68.61	2.10	24.04
129	4	1	2	49.2	48.8	40.7	68.46	2.09	23.79
130	4	1	2	47.9	47.7	38.1	68.24	2.40	24.17

131	4	1	2	48.5	48.1	40.0	69.68	1.83	23.21
132	4	1	2	48.1	47.8	39.1	68.46	2.09	23.94
133	4	2	2	53.0	52.3	48.7	74.76	0.38	13.90
134	4	2	2	54.4	53.8	50.3	75.27	0.42	13.77
135	4	2	2	54.5	53.8	50.4	75.08	0.41	13.78
136	4	2	2	55.0	54.3	50.6	74.76	0.38	14.12
137	4	2	2	54.5	53.9	50.1	74.95	0.67	14.00
138	4	2	2	54.0	53.4	49.7	74.70	0.66	13.90
139	4	3	2	47.0	46.4	39.0	68.17	0.80	20.31
140	4	3	2	46.8	46.3	38.9	67.95	0.79	20.51
141	4	3	2	47.0	46.5	39.3	68.02	0.47	20.35
142	4	3	2	46.9	46.4	39.2	67.20	0.73	20.71
143	4	3	2	47.5	46.9	39.5	67.58	0.43	20.31
144	4	3	2	47.9	47.2	40.3	67.95	0.79	20.22
145	1	1	3	51.0	51.5	39.4	63.92	3.34	23.22
146	1	1	3	51.4	51.9	40.7	64.40	3.34	23.38
147	1	1	3	52.2	52.7	41.6	65.20	3.68	23.41
148	1	1	3	50.9	51.5	39.3	64.00	3.69	24.05
149	1	1	3	51.6	52.1	41.0	64.32	3.34	23.41
150	1	1	3	51.2	51.8	39.8	64.16	3.69	24.33
151	1	2	3	62.9	62.4	56.1	72.30	0.48	15.55
152	1	2	3	63.0	62.5	57.6	72.10	0.47	15.32
153	1	2	3	63.0	62.4	56.1	71.49	0.42	15.99
154	1	2	3	63.1	62.6	56.7	72.10	0.47	15.93
155	1	2	3	63.1	62.6	56.6	71.96	0.46	15.94
156	1	2	3	63.1	62.6	56.6	71.96	0.46	15.94
157	1	3	3	46.2	45.9	37.5	62.76	1.15	19.36
158	1	3	3	46.2	45.9	38.1	63.34	1.18	18.89
159	1	3	3	46.1	45.7	36.9	63.34	1.18	19.71
160	1	3	3	46.1	45.8	37.3	62.93	1.16	18.99
161	1	3	3	45.5	45.1	36.2	62.68	1.51	19.05
162	1	3	3	46.4	46.1	37.0	63.18	1.17	19.26
163	2	1	3	41.1	41.8	29.5	65.52	2.32	19.78
164	2	1	3	40.9	41.5	29.4	64.96	2.31	19.61
165	2	1	3	41.1	41.7	29.8	66.06	2.34	18.89
166	2	1	3	40.6	41.3	29.0	66.37	2.35	19.42
167	2	1	3	41.2	41.9	29.5	64.65	2.65	19.85
168	2	1	3	41.7	42.4	30.0	66.29	2.35	19.14
169	2	2	3	50.4	49.3	44.6	68.97	-0.41	11.90
170	2	2	3	51.1	50.1	45.4	69.26	-0.39	12.14
171	2	2	3	51.2	50.1	45.7	70.04	-0.62	11.65
172	2	2	3	50.7	49.6	45.1	70.80	-0.24	11.3
173	2	2	3	51.2	50.1	45.6	70.80	-0.54	11.54
174	2	2	3	52.1	51.0	46.3	69.40	-0.37	12.02
175	2	3	3	38.3	38.3	29.2	65.28	1.29	16.50
176	2	3	3	38.6	38.5	29.6	63.34	1.18	17.45
177	2	3	3	38.8	38.8	29.7	63.26	1.54	17.30
178	2	3	3	38.5	38.6	29.3	63.92	1.57	17.03
179	2	3	3	38.4	38.4	29.5	64.88	1.27	16.56
180	2	3	3	38.4	38.4	29.4	65.20	1.29	16.36
181	3	1	3	42.1	42.7	29.4	64.65	2.99	23.62
182	3	1	3	41.9	42.6	28.8	64.40	2.99	23.21
183	3	1	3	42.0	42.6	28.8	64.49	2.99	23.18
184	3	1	3	41.4	42.0	28.4	65.04	3.00	23.80
185	3	1	3	41.9	42.4	28.4	65.20	3.00	23.91
186	3	1	3	42.6	43.2	29.0	64.88	3.00	23.53
187	3	2	3	55.1	54.0	49.4	71.62	-1.06	12.60
188	3	2	3	55.2	54.1	49.3	71.69	-0.76	12.72
189	3	2	3	55.3	54.2	49.7	72.10	-0.71	12.48
190	3	2	3	55.4	54.3	49.7	71.76	-0.75	12.13
191	3	2	3	55.0	53.9	49.3	72.10	-0.71	12.36
192	3	2	3	54.9	53.8	49.3	72.03	-0.72	12.36
193	3	3	3	37.9	37.7	30.3	62.17	0.75	18.01
194	3	3	3	37.0	36.7	28.9	61.74	0.72	18.61
195	3	3	3	38.1	37.9	30.7	62.59	0.77	17.43
196	3	3	3	38.3	38.1	30.6	61.66	1.09	18.13
197	3	3	3	37.7	37.5	29.9	62.00	0.73	17.39
198	3	3	3	37.6	37.4	29.5	62.59	1.14	17.43
199	4	1	3	49.4	49.0	41.1	65.12	2.66	24.44
200	4	1	3	48.0	47.6	39.3	64.57	2.99	24.16
201	4	1	3	48.9	48.5	39.4	64.81	2.99	24.92
202	4	1	3	50.0	49.5	41.9	64.81	2.99	24.75
203	4	1	3	49.1	48.7	41.0	65.04	2.65	24.48

204	4	1	3	48.5	48.1	39.7	64.81	2.65	24.41
205	4	2	3	54.5	53.8	49.7	71.89	0.15	13.30
206	4	2	3	53.9	53.2	49.5	72.30	0.19	13.17
207	4	2	3	54.7	54.1	50.1	72.16	0.47	13.41
208	4	2	3	54.4	53.7	50.2	72.70	0.22	13.28
209	4	2	3	53.2	52.5	49.1	72.03	0.17	13.18
210	4	2	3	54.1	53.4	49.7	72.10	0.17	13.29
211	4	3	3	46.3	45.7	38.1	64.16	0.88	20.14
212	4	3	3	46.1	45.5	37.7	64.49	0.90	20.37
213	4	3	3	47.2	46.7	38.9	63.84	0.85	20.39
214	4	3	3	47.3	46.8	39.2	64.24	0.88	20.28
215	4	3	3	47.2	46.6	39.2	64.49	0.90	20.53
216	4	3	3	47.8	47.2	39.9	64.16	1.23	20.30
217	1	1	4	52.4	52.8	42.4	61.48	2.96	23.49
218	1	1	4	51.2	51.7	39.8	61.40	3.71	23.72
219	1	1	4	51.2	51.7	40.1	61.05	3.33	22.74
220	1	1	4	51.4	52.0	39.7	61.48	3.71	23.87
221	1	1	4	51.0	51.6	39.3	61.22	3.33	24.36
222	1	1	4	51.6	52.2	41.1	61.05	3.33	22.93
223	1	2	4	62.6	62.1	56.1	68.97	-0.10	14.96
224	1	2	4	62.9	62.4	56.4	68.97	-0.10	15.22
225	1	2	4	62.6	62.0	56.1	68.90	0.22	15.09
226	1	2	4	62.9	62.4	56.4	68.83	0.21	15.10
227	1	2	4	63.0	62.4	56.4	68.75	-0.11	15.24
228	1	2	4	63.5	62.9	56.5	69.19	0.24	15.72
229	1	3	4	46.1	45.9	37.0	60.61	1.41	17.86
230	1	3	4	45.4	45.1	36.5	60.52	1.41	18.40
231	1	3	4	45.7	45.4	37.5	60.61	1.41	18.03
232	1	3	4	45.4	45.1	36.6	60.61	1.41	18.03
233	1	3	4	46.0	45.7	37.8	60.61	1.03	19.08
234	1	3	4	45.2	44.9	36.6	59.89	1.38	18.20
235	2	1	4	40.7	41.3	28.9	63.84	1.57	18.14
236	2	1	4	40.7	41.4	29.1	62.93	1.89	18.34
237	2	1	4	41.4	42.0	30.1	65.98	1.67	17.56
238	2	1	4	42.0	42.7	30.8	67.05	1.38	16.53
239	2	1	4	41.6	42.2	29.6	63.26	1.90	17.94
240	2	1	4	41.4	42.0	30.1	65.59	1.65	17.19
241	2	2	4	50.5	49.4	44.9	67.50	-0.56	10.63
242	2	2	4	49.9	48.9	44.1	67.65	-0.21	10.38
243	2	2	4	50.7	49.7	45.0	67.50	-0.56	10.25
244	2	2	4	51.3	50.2	45.6	68.10	-0.50	10.14
245	2	2	4	51.0	49.8	45.3	67.43	-0.23	10.12
246	2	2	4	51.8	50.8	46.1	67.73	-0.21	10.25
247	2	3	4	38.1	38.2	29.0	64.40	0.89	15.73
248	2	3	4	37.7	37.8	28.8	61.31	1.45	16.03
249	2	3	4	38.8	38.9	29.7	62.34	1.50	15.71
250	2	3	4	38.4	38.2	28.7	66.29	0.67	15.08
251	2	3	4	37.5	37.6	28.5	64.00	0.86	15.64
252	2	3	4	39.2	39.2	30.2	63.59	0.84	15.54
253	3	1	4	40.7	41.4	27.2	62.68	2.61	21.95
254	3	1	4	42.2	42.8	29.0	63.01	2.61	21.66
255	3	1	4	41.3	42.0	28.2	63.67	2.63	22.63
256	3	1	4	42.4	43.0	29.3	63.51	2.62	21.32
257	3	1	4	41.6	42.2	28.4	63.76	2.27	21.92
258	3	1	4	41.0	41.7	27.7	63.43	2.62	21.52
259	3	2	4	54.9	53.8	49.1	69.33	-0.69	11.53
260	3	2	4	55.2	54.1	49.4	69.04	-1.04	11.28
261	3	2	4	54.5	53.4	48.6	69.54	-0.99	11.28
262	3	2	4	55.2	54.1	49.6	69.33	-0.69	11.28
263	3	2	4	55.0	54.0	49.7	69.54	-0.99	10.80
264	3	2	4	55.1	54.0	49.6	69.47	-0.68	11.04
265	3	3	4	36.4	36.2	28.4	60.34	1.01	16.71
266	3	3	4	38.7	38.5	31.4	60.52	0.63	16.67
267	3	3	4	37.0	36.8	28.5	60.16	1.00	17.26
268	3	3	4	37.8	37.7	29.7	60.43	1.02	16.69
269	3	3	4	37.7	37.5	29.8	61.91	1.10	15.62
270	3	3	4	37.3	37.1	29.1	60.87	1.04	17.11
271	4	1	4	48.2	47.8	39.6	62.51	3.33	23.98
272	4	1	4	47.0	46.7	38.2	62.42	2.97	23.83
273	4	1	4	49.2	48.8	40.7	62.76	2.97	24.05
274	4	1	4	47.7	47.4	38.5	62.51	2.97	23.79
275	4	1	4	49.1	48.7	40.3	62.85	2.97	23.83
276	4	1	4	48.7	48.3	39.5	62.85	3.33	24.01

277	4	2	4	54.0	53.4	49.3	70.11	0.31	12.62
278	4	2	4	54.4	53.8	50.0	70.32	0.02	12.38
279	4	2	4	55.4	54.8	51.1	70.39	0.03	12.38
280	4	2	4	54.2	53.6	50.1	70.66	0.05	12.49
281	4	2	4	54.7	54.0	50.7	70.53	0.04	12.37
282	4	2	4	54.4	53.7	50.0	70.53	0.34	12.62
283	4	3	4	46.8	46.3	38.6	61.48	1.08	18.85
284	4	3	4	47.2	46.6	39.1	61.57	1.08	18.83
285	4	3	4	47.4	46.9	39.5	61.83	1.10	19.10
286	4	3	4	47.6	47.1	40.0	62.00	1.11	19.06
287	4	3	4	47.1	46.6	39.1	62.00	1.11	19.23
288	4	3	4	47.6	47.1	39.3	61.83	1.10	18.93

Appendix D

Subjective Observer Sample Rankings For Shade A3.5

SAMPLE	BRAND*	DENTIN	Observers						
			EI	MS	RS	DR	BB	SK	JB
2	M	0.0	1	1	2	1	3	1	2
76	M	0.3	2	3	5	2	5	3	5
149	M	0.6	1	1	4	3	3	4	4
221	M	0.9	4	1	4	1	1	2	1
24	C	0.0	1	2	1	1	3	1	2
91	C	0.3	2	3	4	4	4	5	3
163	C	0.6	3	4	4	3	5	3	2
237	C	0.9	1	4	3	3	4	2	2
41	J	0.0	2	3	4	4	5	3	5
112	J	0.3	1	2	3	4	2	2	2
186	J	0.6	2	2	3	4	4	4	4
258	J	0.9	5	4	5	4	4	5	4
60	V	0.0	1	1	1	1	1	1	1
129	V	0.3	1	3	4	2	4	2	3
203	V	0.6	2	2	2	2	3	2	3
273	V	0.9	1	2	2	1	1	1	1

* M= Microbond, C= Ceramco II, J= Jelenko, V= Vita VMK 68

Subjective Observer Sample Rankings
For Shade B1

SAMPLE	BRAND*	DENTIN	Observers						
			EI	MS	RS	DR	BB	SK	JB
10	M	0.0	2	2	1	1	3	1	4
80	M	0.3	2	2	1	1	1	1	1
156	M	0.6	1	1	1	1	1	1	1
224	M	0.9	4	1	1	1	1	1	1
30	C	0.0	2	3	3	3	3	5	3
98	C	0.3	1	3	2	3	1	4	2
173	C	0.6	5	4	4	1	5	4	3
246	C	0.9	1	3	2	1	1	5	2
47	J	0.0	3	4	4	4	4	4	5
118	J	0.3	4	4	4	1	2	2	4
192	J	0.6	3	5	3	4	5	5	5
262	J	0.9	4	4	4	4	4	4	2
64	V	0.0	1	2	1	1	3	2	3
135	V	0.3	2	4	2	2	3	1	2
210	V	0.6	2	2	2	1	1	4	2
279	V	0.9	1	1	1	2	2	1	1

* M= Microbond, C= Ceramco II, J= Jelenko, V= Vita VMK 68

Subjective Observer Sample Rankings
For Shade C3

SAMPLE	BRAND*	DENTIN	Observers						
			EI	MS	RS	DR	BB	SK	JB
15	M	0.0	3	3	3	4	3	1	5
90	M	0.3	2	3	4	2	5	3	4
162	M	0.6	3	4	4	3	3	4	3
229	M	0.9	1	1	1	1	1	1	1
35	C	0.0	4	2	2	1	1	1	1
106	C	0.3	2	2	2	1	1	3	2
179	C	0.6	4	4	5	4	4	5	4
251	C	0.9	1	5	3	5	5	4	4
53	J	0.0	2	3	1	3	3	1	3
123	J	0.3	3	3	4	1	1	1	1
193	J	0.6	5	3	5	3	2	3	1
265	J	0.9	4	3	4	1	4	2	3
69	V	0.0	1	2	2	4	4	5	5
140	V	0.3	4	4	4	2	3	2	4
214	V	0.6	4	3	4	2	2	4	3
288	V	0.9	5	3	3	1	1	1	1

* M= Microbond, C= Ceramco II, J= Jelenko, V= Vita VMK 68